



Principles of Modeling for Cyber-Physical Systems

Fall 2018
CS 6501-003 / SYS 6581-005/600

Madhur Behl

Computer Science
Systems and Information Engineering

Ok, cool title slide...but what is this course about ?

Principles of Modeling for Cyber-Physical Systems

Lets break it down..

1. What are Cyber-Physical Systems ?
2. What do you really mean by modeling ?
3. What principles am I going to learn about ?

and also...who are you, again ?

Meet your instructor

Madhur Behl

Physicist at ❤
Cyber-Physicist by profession

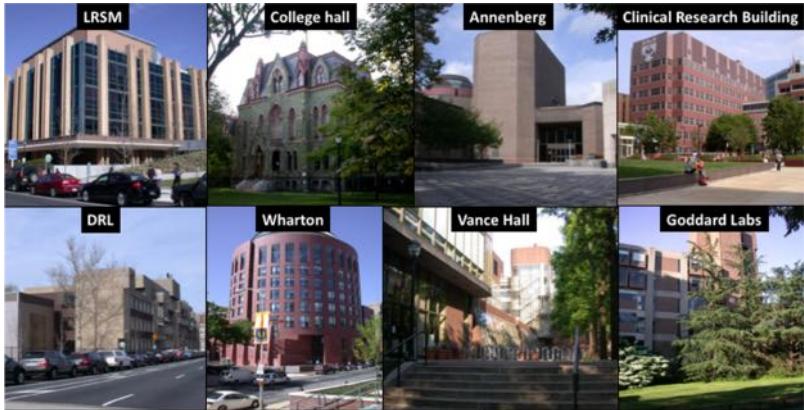
Assistant Professor
Computer Science,
Systems and Information Engineering.



PhD, University of Pennsylvania (2015)
Co-Founder @ Flexergy AI

What do I do..

Modeling, simulation, control, optimization, and implementation of Cyber-Physical System



Cyber-Physical Energy Systems



Internet of things

Data Predictive Control:

Interfacing machine learning suitable for predictive control.

DeepExplainations:

Answering open-ended queries using procedural generation and interpretable models.

DeepRacing AI:

Algorithms for operating autonomous cars at the limits of their control



Safety of Autonomous Vehicles



Critical Infrastructures & Smart Cities

Today's lecture

- Course logistics (5-7 mins)
- Course introduction (the interesting stuff !)

Course Logistics

- **Timings:** Tue & Thu 2:00pm – 3:15pm,
- **Location:** Thornton Hall D222
- **Course website:** https://linklab-uva.github.io/modeling_cps/index.html
 - All lectures notes/slides/assignments/videos will be posted on this website.
- **Piazza:** <https://piazza.com/virginia/fall2018/cs6501003sys6581005/home>
- **Prerequisites:**
 - Familiarity with Matlab / Simulink.
 - Some programming experience, Python is a plus.
 - Mathematical maturity (differential equations, matrix operations, some calculus, probability distributions)

Grading

- No midterm, No final exam.
- The course has three modules (more on this later). Each module is equally weighted.
 - Energy CPS, Medical CPS, and Automotive CPS
- ~4 worksheets in each module, comprising of:
 - Problem sets
 - Coding/implementation assignments
- 2 late homework submissions permitted – No questions asked.
 - Should not be more than 1 day late. Will result in deduction in grade for each day thereafter.
- Abide by the UVA honor system. Discussion on assignments is allowed but absolutely no code/solution sharing !

Your responsibilities.

- Attend the lectures (in-person for on-grounds students)
- Check the course website for announcements, and assignments.
- Ask questions ! (in person, and on Piazza)
 - Ask, disagree, debate..
- Live streamed office hours will be held for online CGEP students.

Office Hours

- **Timings:** Monday 2-3pm, or by appointment.
- **Location:** Link Lab Room 265 [Olsson Hall 2nd floor]
- Feel free to stop by:
 - To discuss course assignments or lectures.
 - Research opportunities.

what is this course about ?

Principles of Modeling for **Cyber-Physical Systems**

Lets break it down..

1. What are Cyber-Physical Systems ?
2. What do you really mean by modeling ?
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Cyber-Physical Systems

Deeply integrating
computation, communication, and control

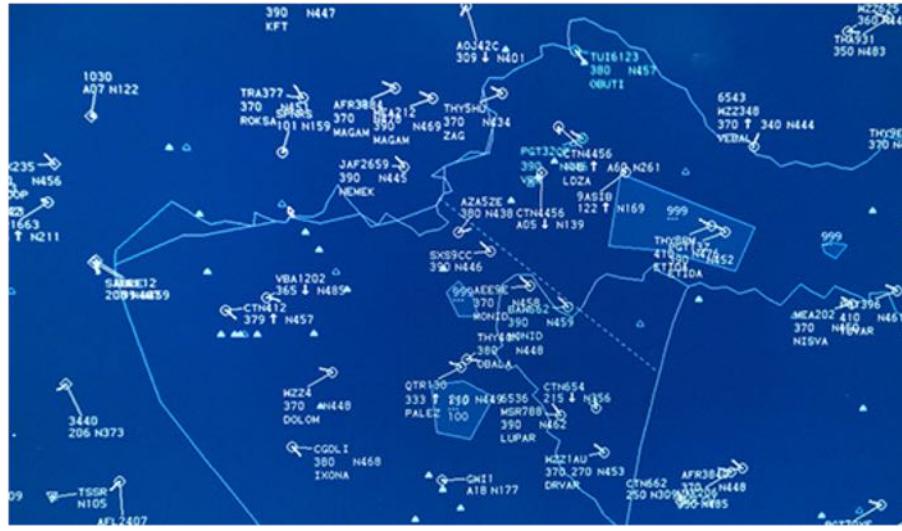
into **physical systems**

- ❑ **Physical** = some tangible, physical device or system + environment
- ❑ **Cyber** = computational + communicational

Application domains: Transportation



Faster, safer, more
energy-efficient air
travel

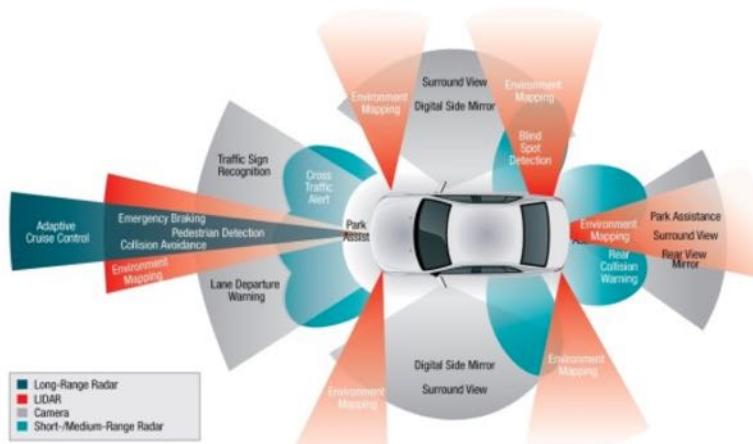


Improved use of
airspace

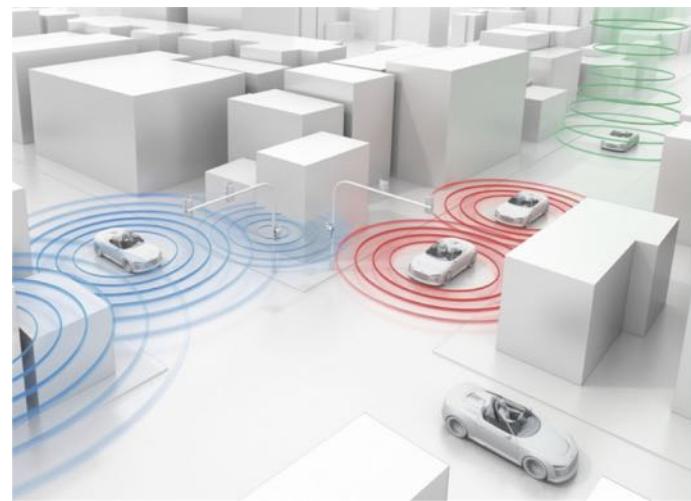


Autonomous unmanned
drones

Application domains: Transportation



Safety, security, and control of autonomous cars



- Connected vehicles.
- Autonomous fleets/ride sharing.
- Traffic management



Application domains: Energy



- Smart buildings.
- Energy-efficient operation.
- Smart homes.
- EV charging/solar rooftops
- Reliable and resilient electricity grid.
- Micro grids.

Application domains: Healthcare + Biomedical

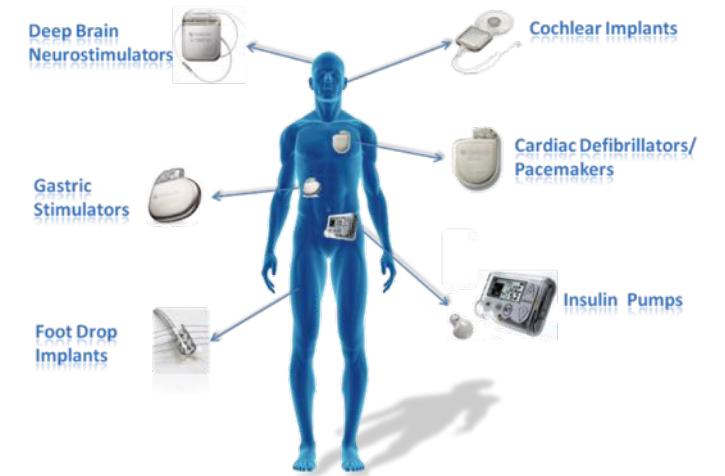


- Electronic patient record management.
- In home healthcare delivery.



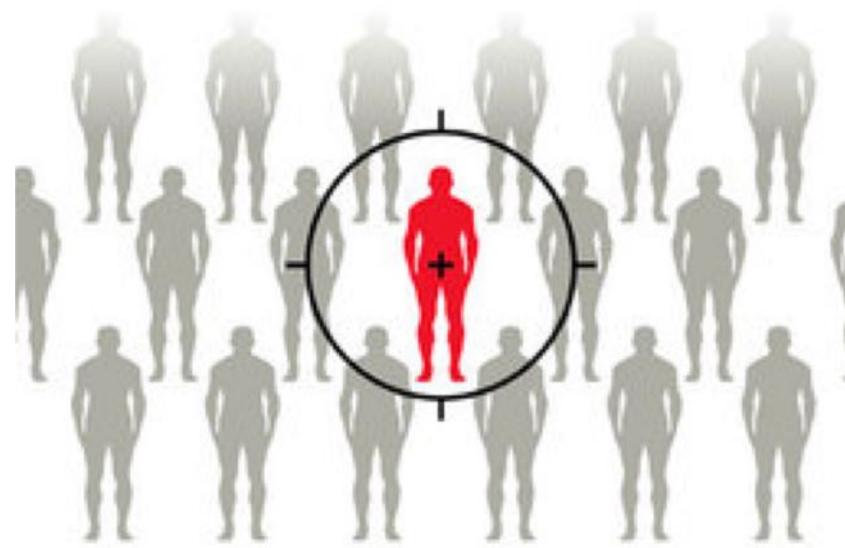
Health and well being monitoring devices.

WIRELESS IMPLANTABLE MEDICAL DEVICES



Safety, and security of medical devices and heath management systems.

Application domains: Healthcare + Biomedical



- Internal and external prosthetics

Gene, protein expression.
Systems biology.

Application domains: Critical Infrastructure



- Water & waste management.
- Storm-water/flood control.

Structural health
monitoring

Utility infrastructure- Gas,
Electricity, Steam.

Application domains: ... and many more



Agriculture



Manufacturing

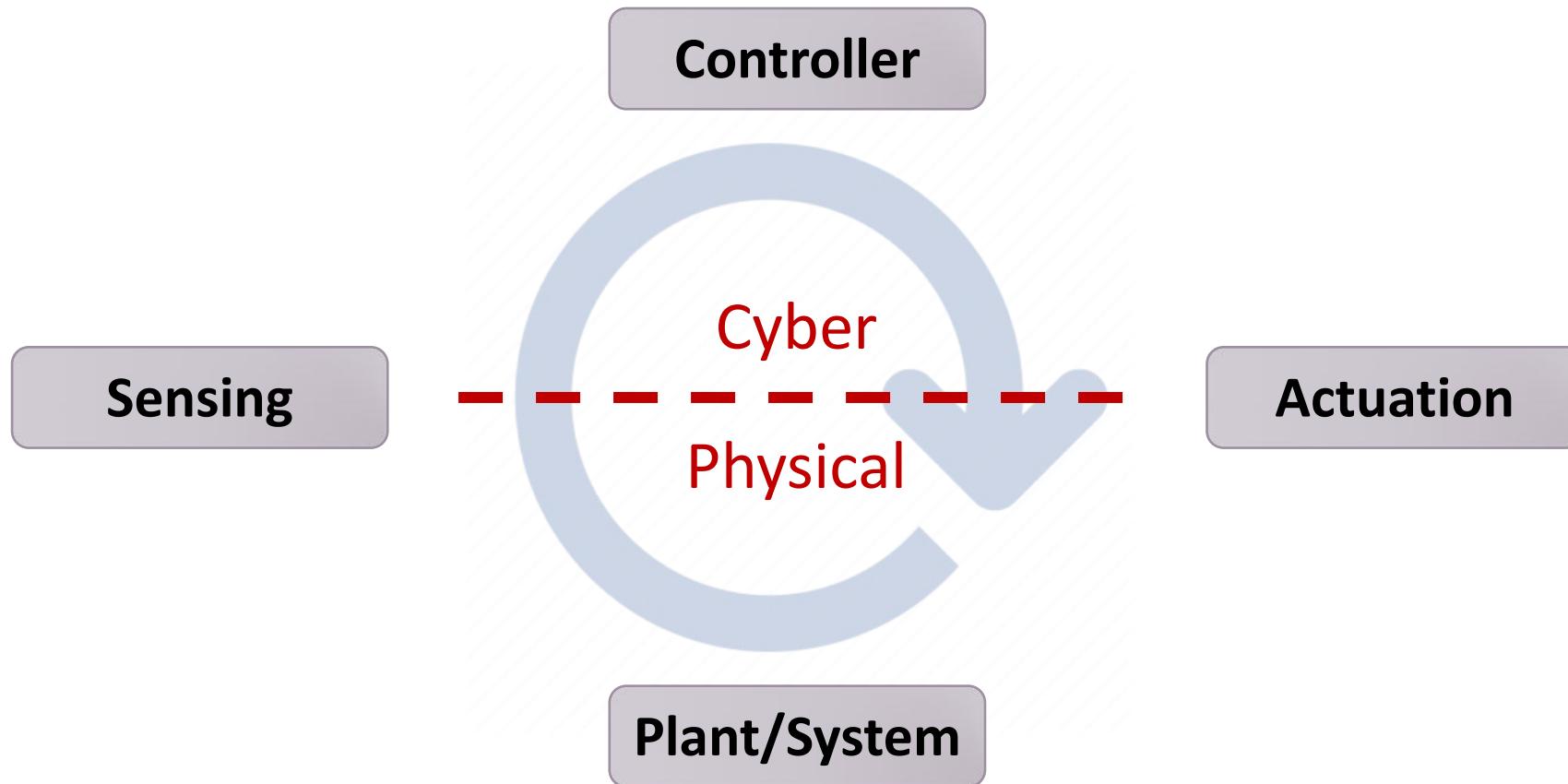


Industrial Control

Characteristics of CPS

- Pervasive computation, sensing and control
- Networked at multi- and extreme scales
- Dynamically reorganizing/reconfiguring
- High degrees of automation
- Dependable operation with *potential* requirements for high assurance of reliability, safety, security and usability
 - With / without human in-the-loop
 - Conventional and unconventional substrates / platforms

Closing the loop



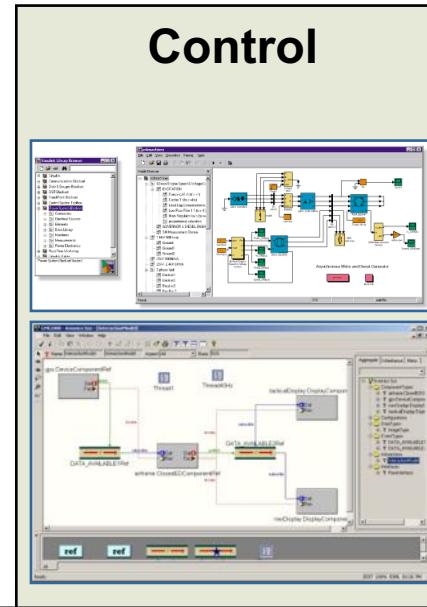
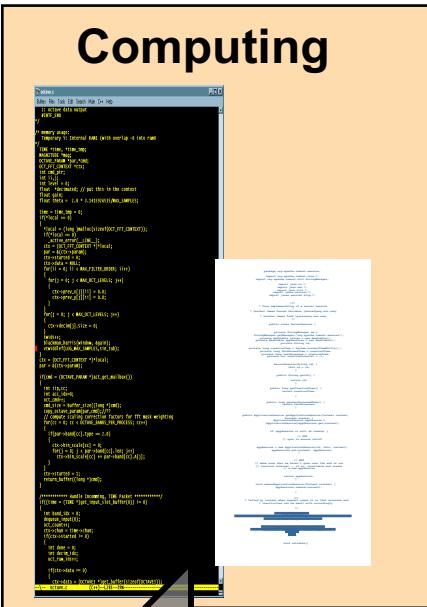
Cyber-Physical Systems - Goals

Transform how we interact with the physical world

Fusion of physical and computational sciences

Produce significant impact on society

Why is CPS hard ?



Crosses Interdisciplinary Boundaries

Why is CPS hard ?

- Disciplinary boundaries need to be realigned
- New **fundamentals** need to be created
- New **technologies and tools** need to be developed
- Education need to be restructured

Why is CPS hard ?

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Hmmm, I wonder if there is a course which is trying to achieve this?

what is this course about ?

Principles of **Modeling** for Cyber-Physical Systems

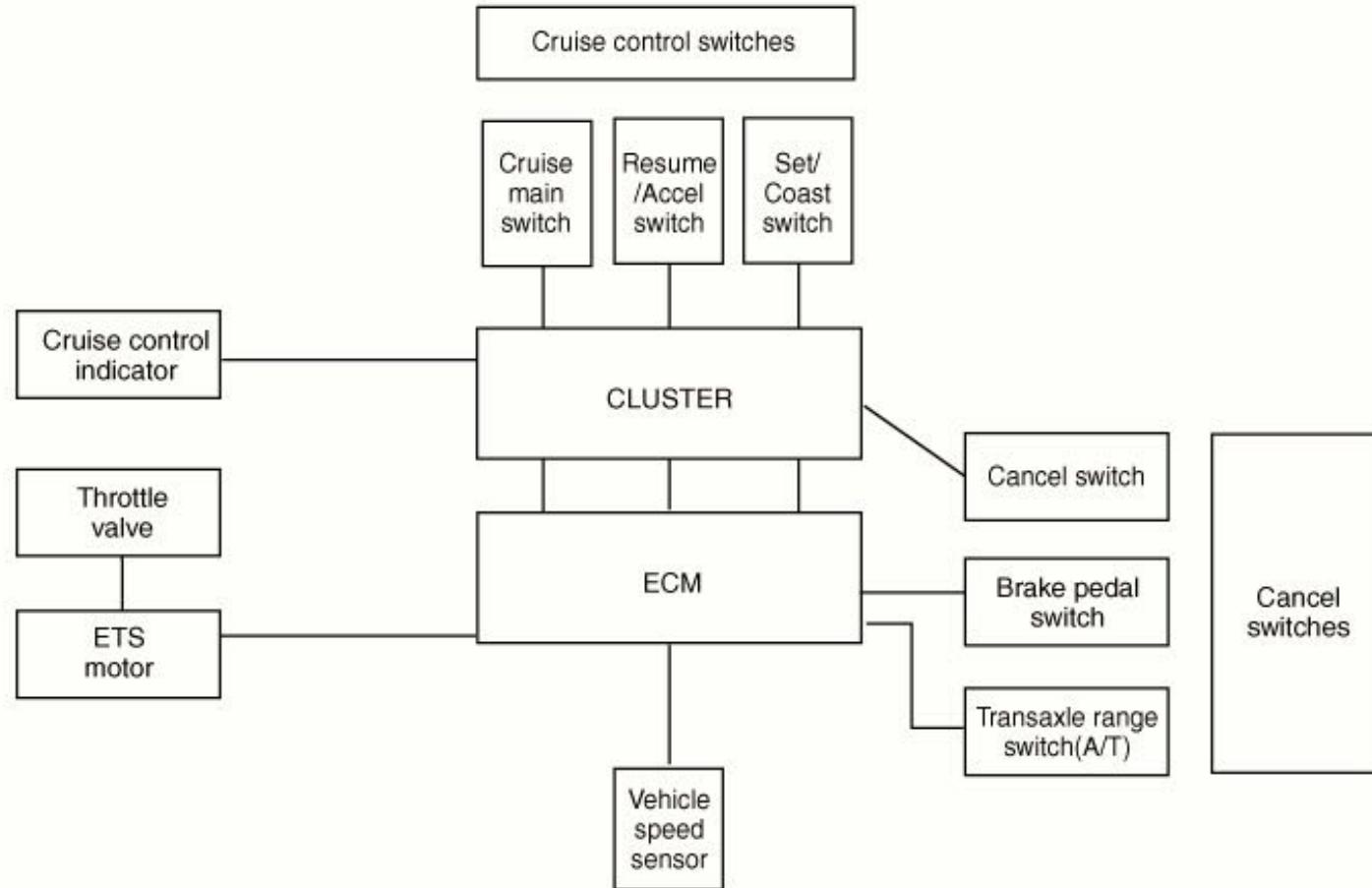
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3. What principles am I going to learn about ?

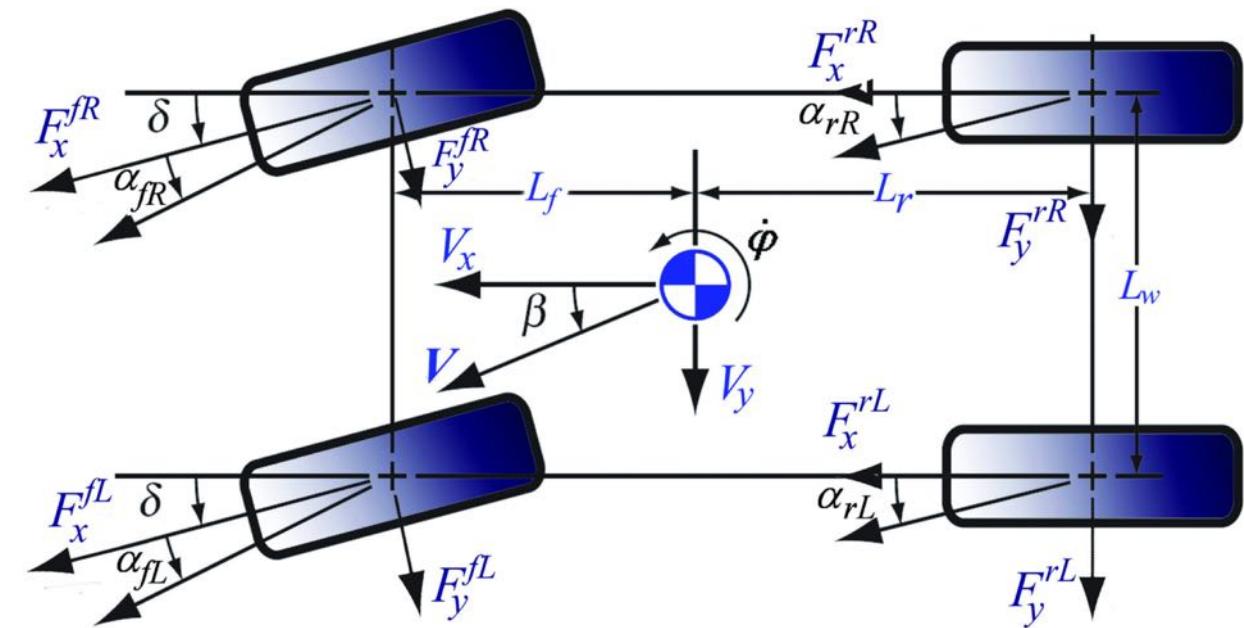
Modeling types: Physical modeling



Modeling types: Functional/compositional modeling

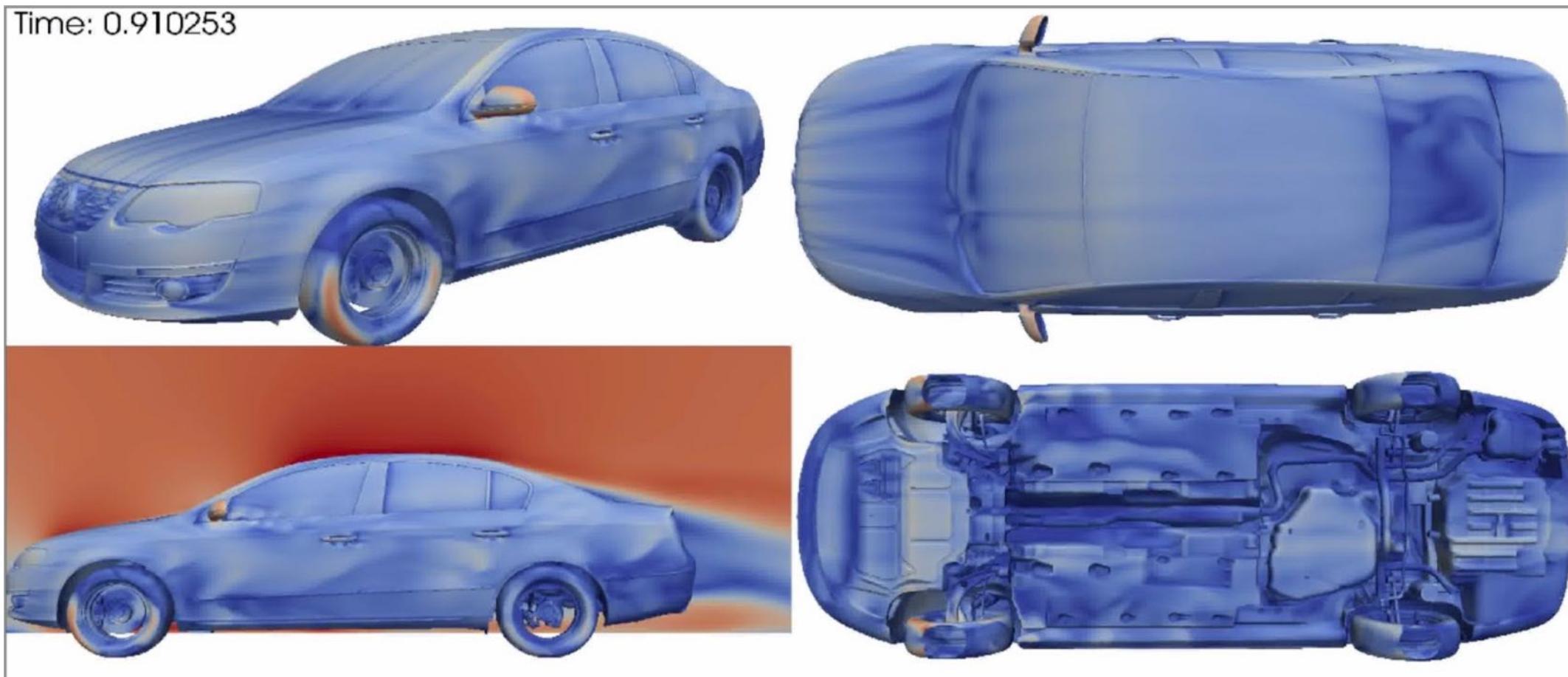


Modeling types: Mathematical modeling

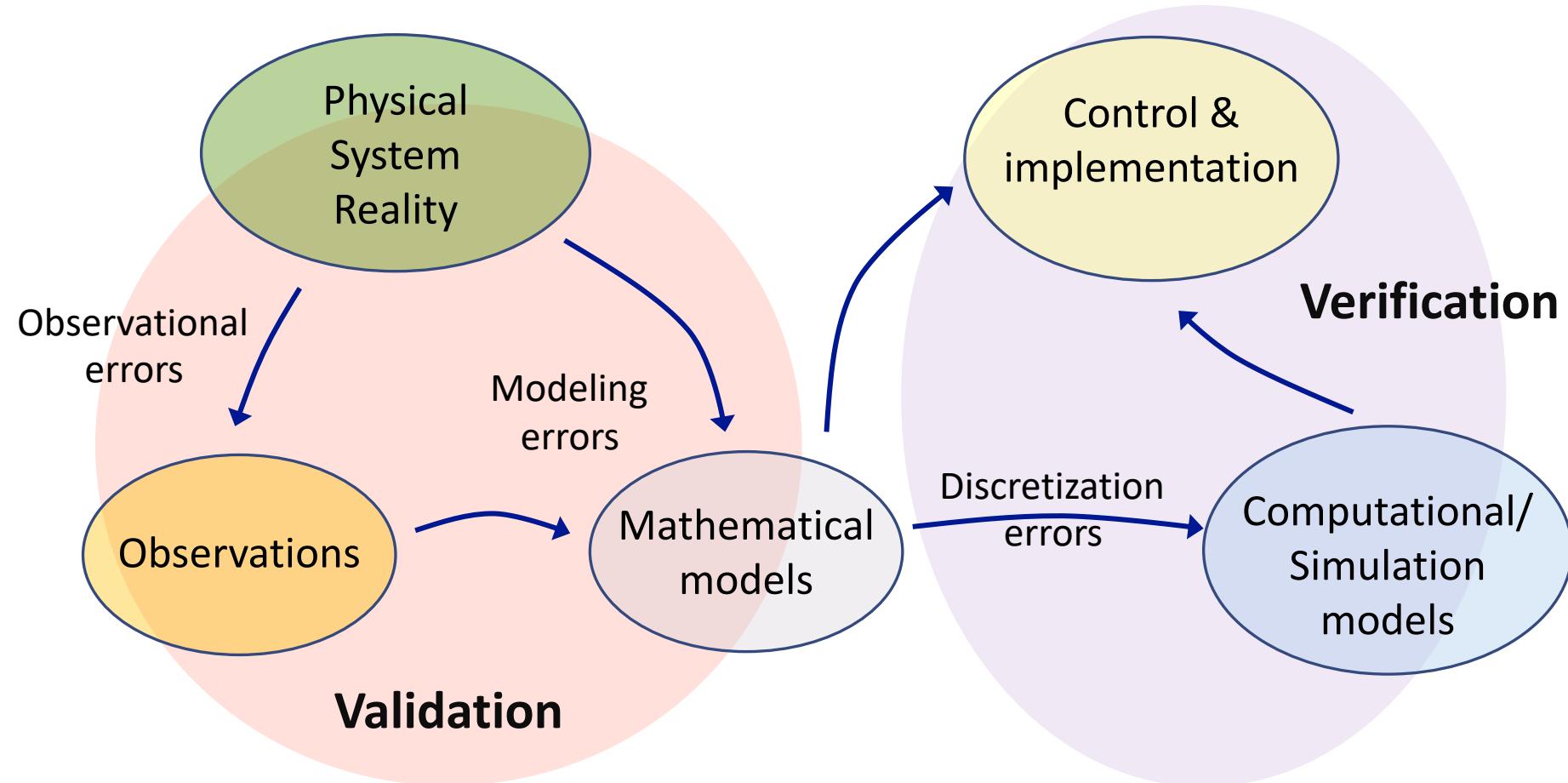


$$\begin{aligned}\dot{v}_x &= \frac{1}{m} \left[(F_x^{fL} + F_x^{fR}) \cos \delta - (F_y^{fL} + F_y^{fR}) \sin \delta + (F_x^{rL} + F_x^{rR}) + \dot{\phi} v_y \right], \\ \dot{v}_y &= \frac{1}{m} \left[(F_y^{fL} + F_y^{fR}) \cos \delta + (F_x^{fL} + F_x^{fR}) \sin \delta + (F_y^{rL} + F_y^{rR}) - \dot{\phi} v_x \right], \\ \dot{\phi} &= \frac{1}{I_\phi} \left(L_f (F_x^{fL} + F_x^{fR}) \sin \delta + L_f (F_y^{fL} + F_y^{fR}) \cos \delta - L_r (F_x^{rL} + F_x^{rR}) \right. \\ &\quad \left. + \frac{L_w}{2} (F_x^{fR} - F_x^{fL}) \cos \delta + \frac{L_w}{2} (F_x^{rR} - F_x^{rL}) + \frac{L_w}{2} (F_y^{fL} - F_y^{fR}) \sin \delta \right),\end{aligned}$$

Modeling types: Computational modeling



A word about mathematical models



“Essentially all models are wrong, but some are useful”

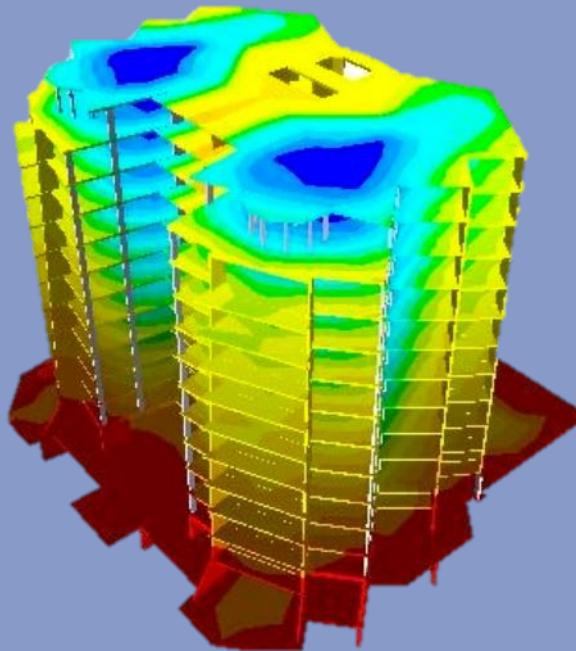
- George E.P. Box (statistician)

....this course is about building useful models.

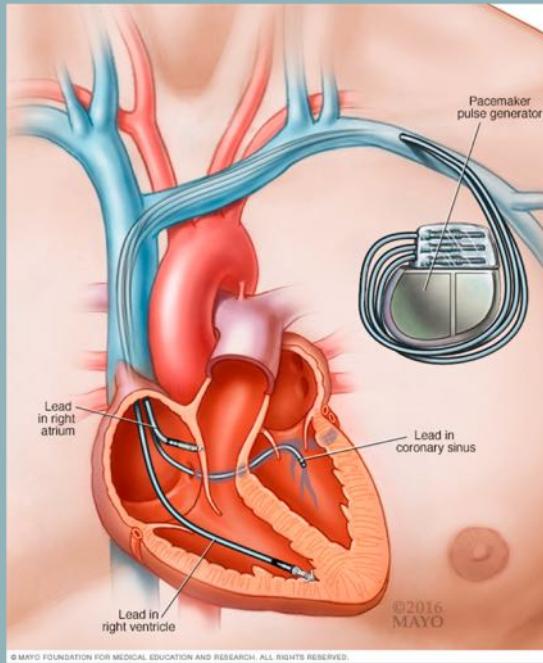
This course: Model development is a skill

- First principles based modeling: White Box.
- Gray box models: With some unknown parameters.
- Black box (data-driven) models.
- State machines and timed automata.

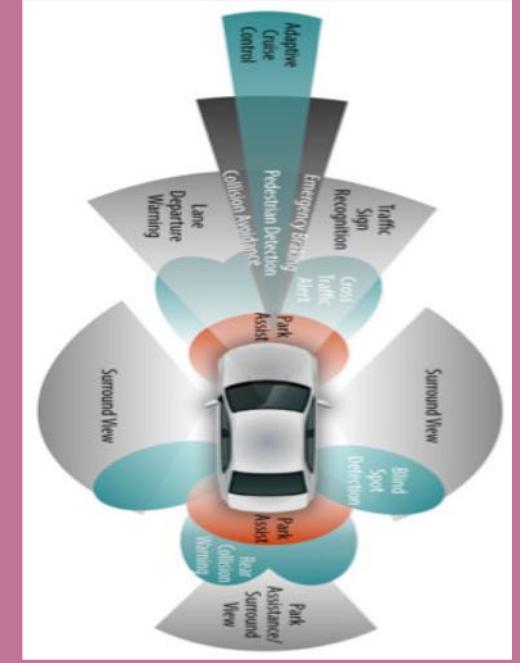
This course: Three CPS domains



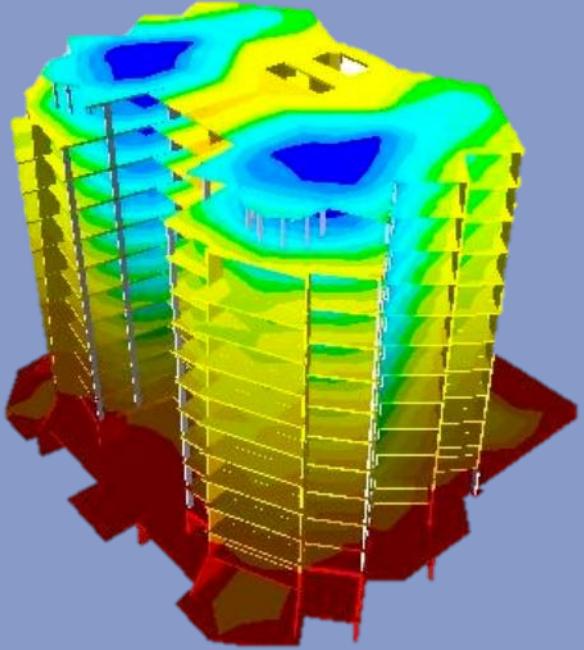
Energy CPS



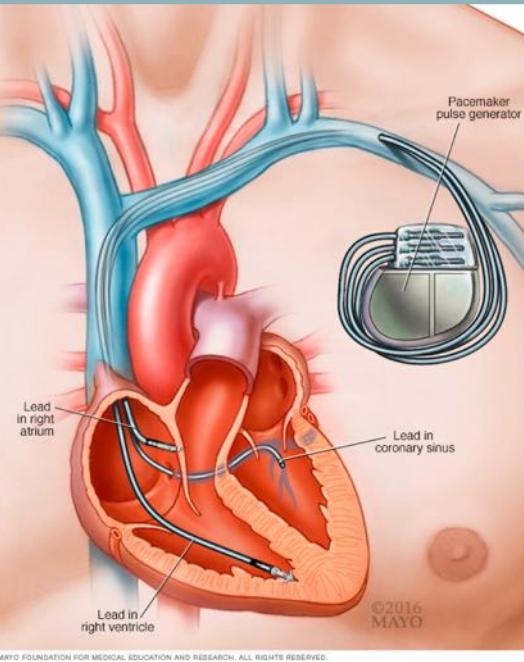
Medical CPS



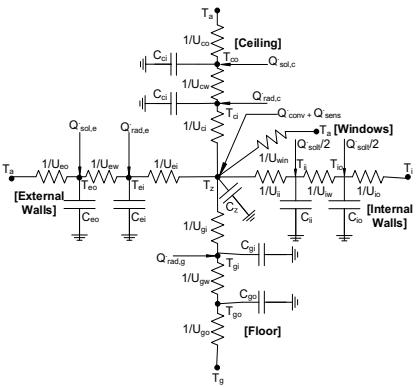
Automotive CPS



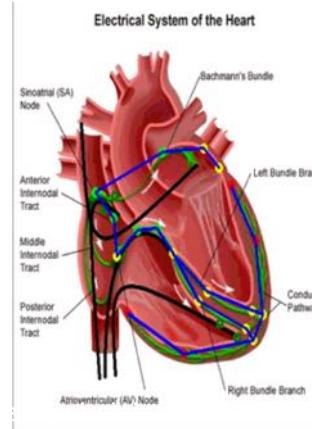
Energy CPS



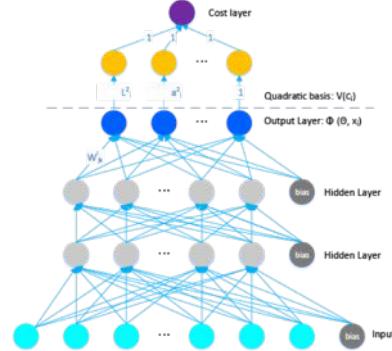
Medical CPS

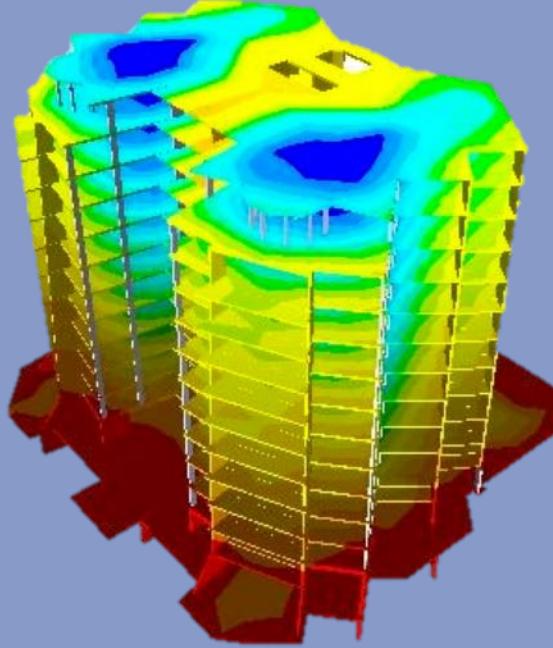


Timed Automata

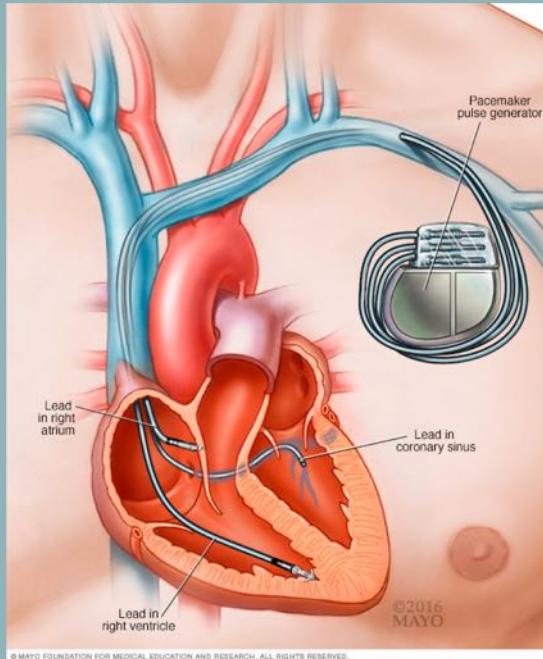


Data-driven

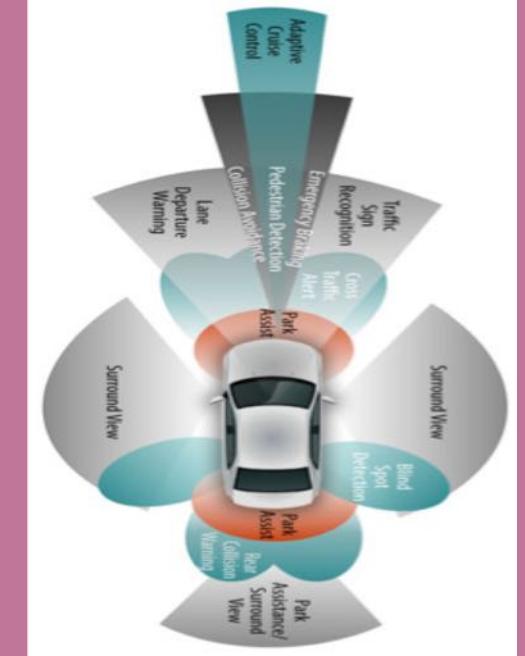




Energy CPS



Medical CPS



Automotive CPS

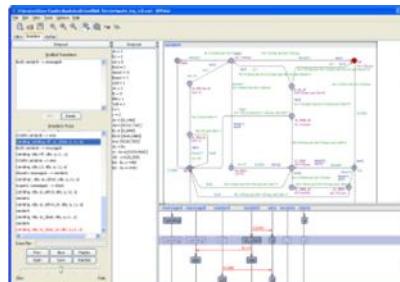


EnergyPlus

Matlab

UPPAAL

Simulink



TensorFlow

Python

Energy CPS Module

2014 Officially Hottest Year on Record

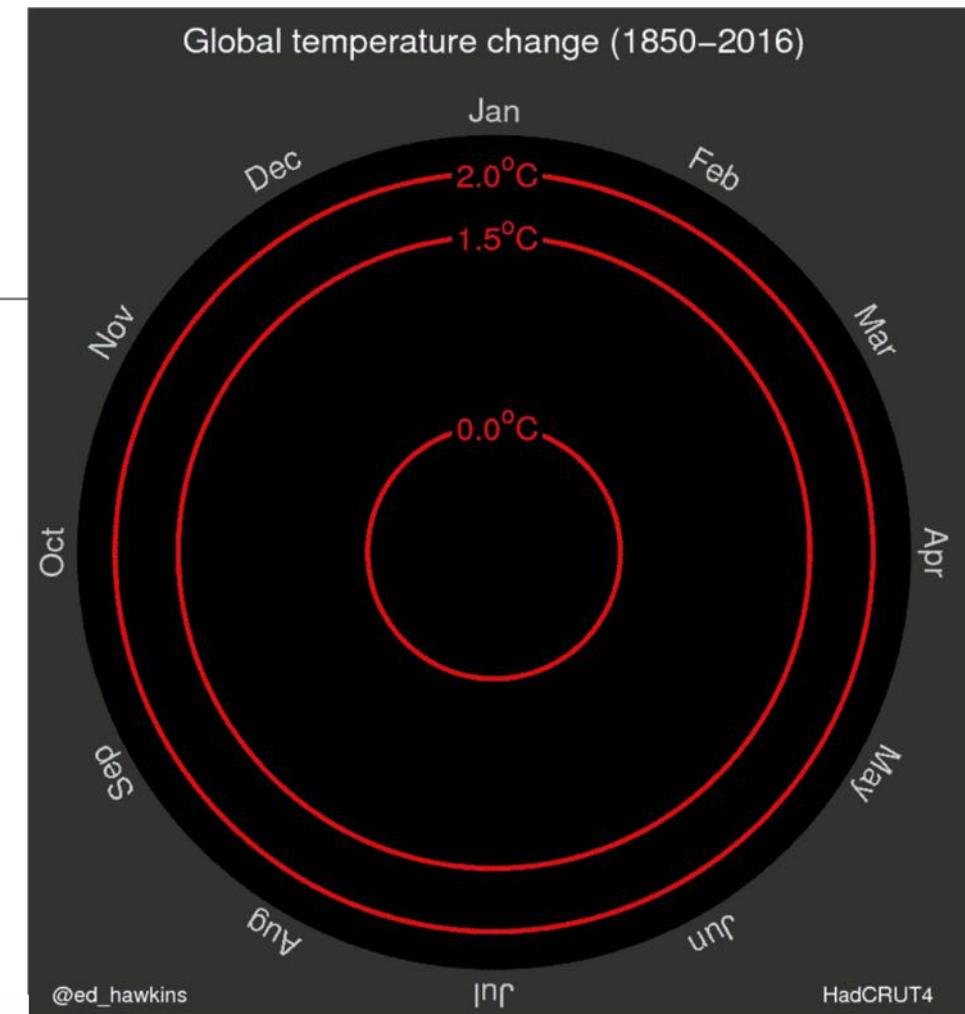
2015 Is Officially the Hottest Year on Record

2016 Was the Hottest Year on Record

CLIMATE

2017 Was the Third Hottest Year on Record for the U.S.

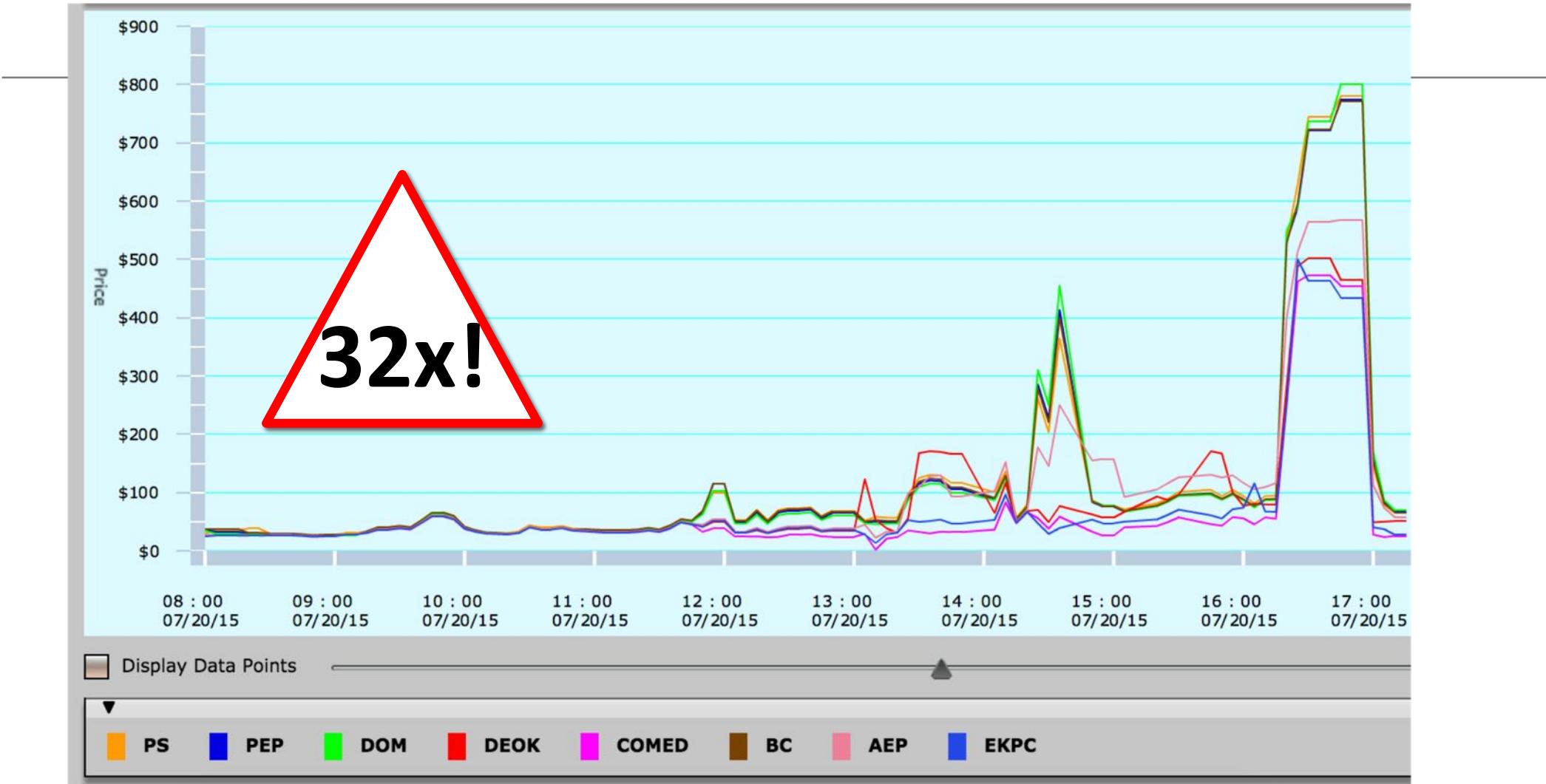
2018 is on pace to be the 4th-hottest year on record



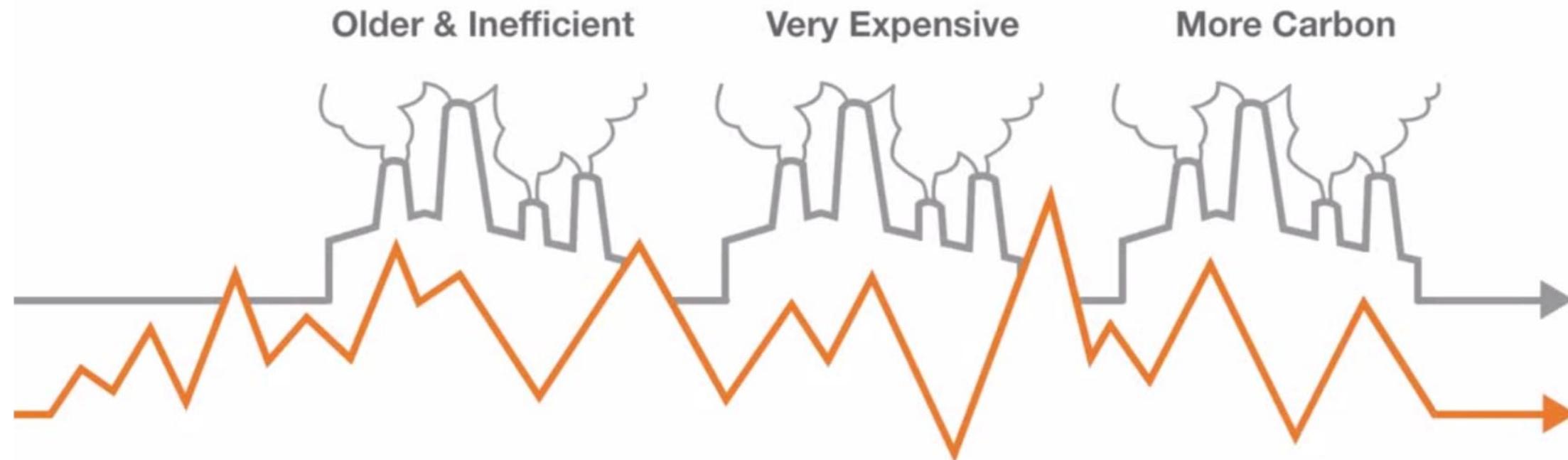
Price Volatility: Summer peak

Nominal price: \$25/MWh

Peak Price: \$800/MWh



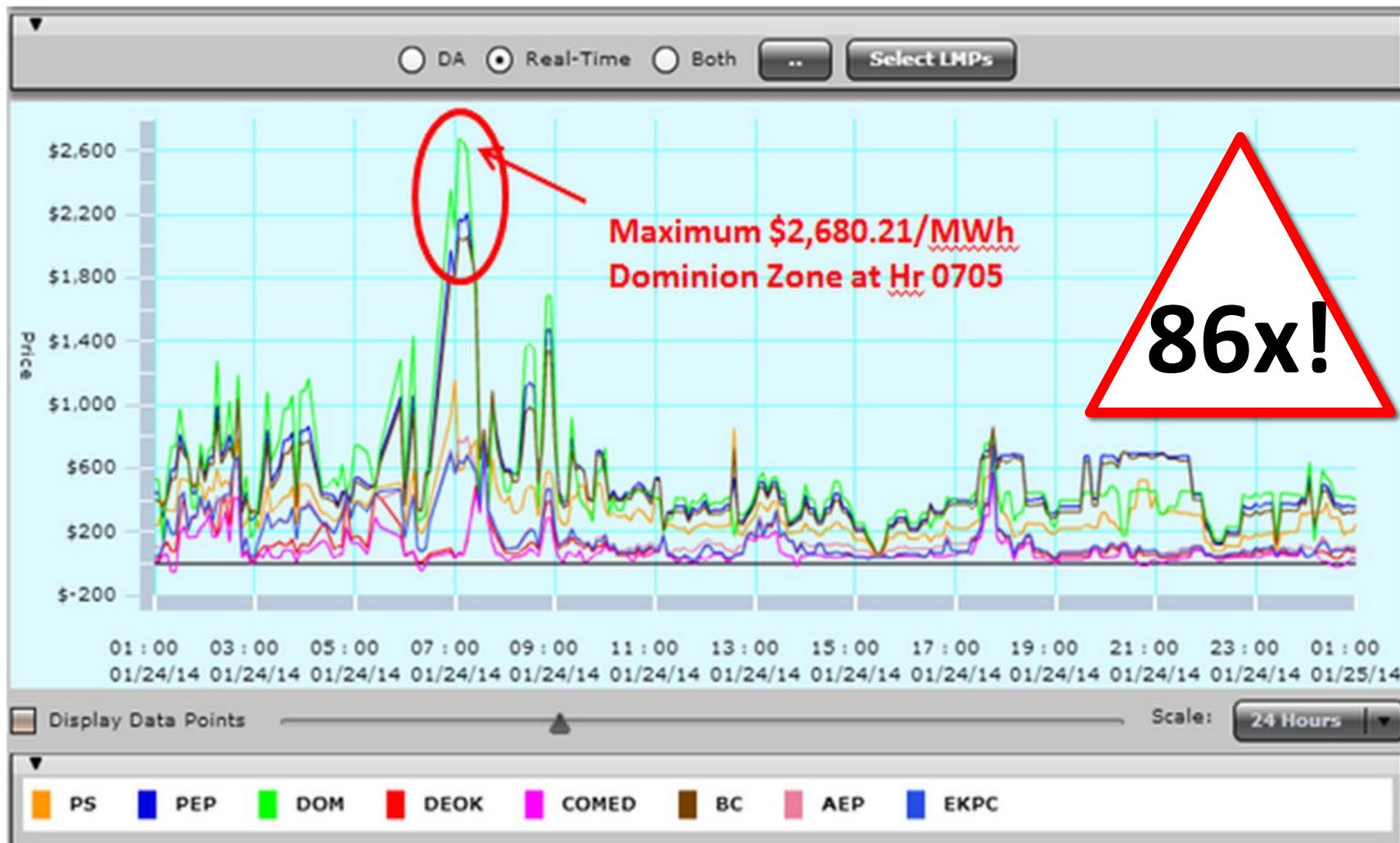
“All kilowatts are not created equally”



Price Volatility: Winter peak

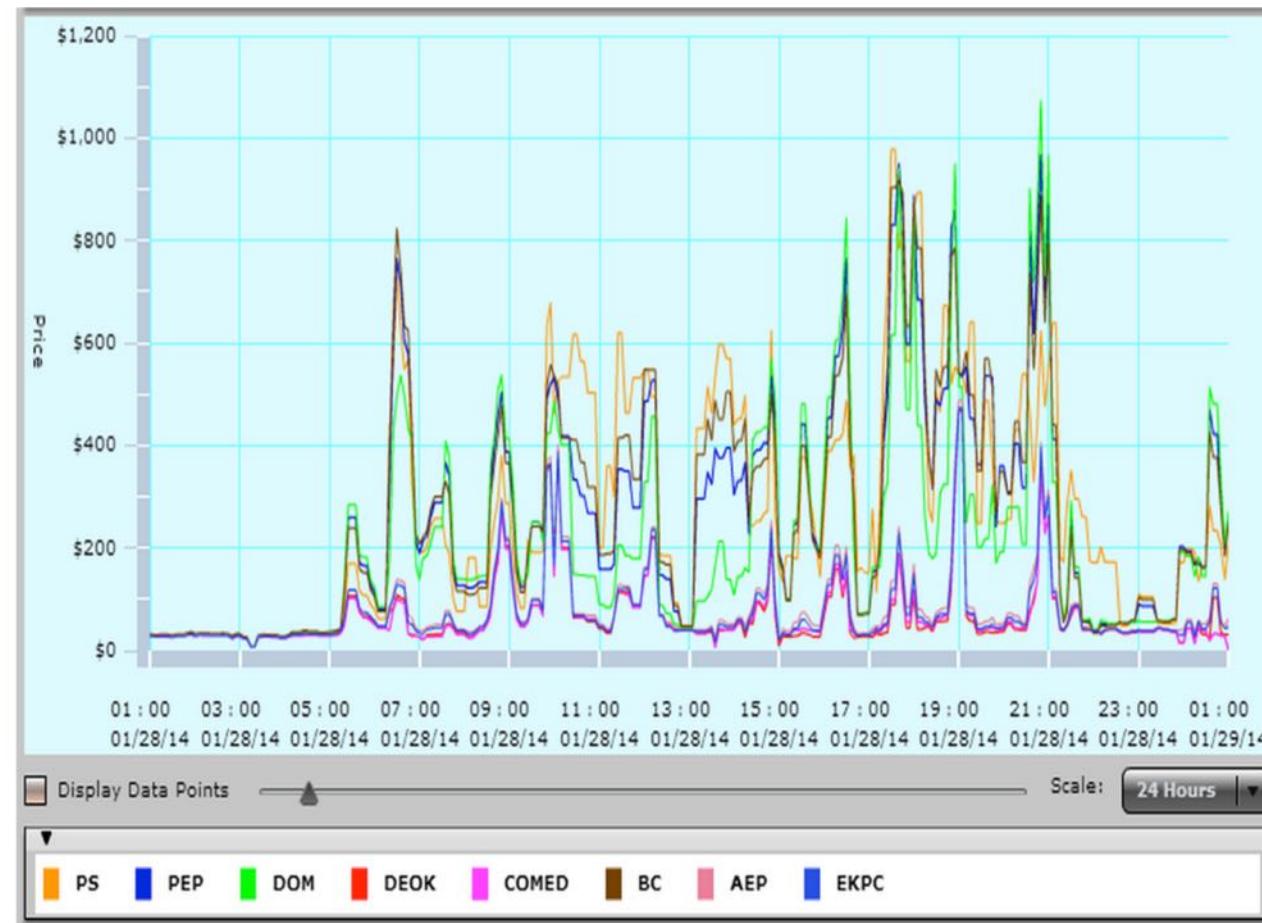
Nominal price: \$31.21/MWh

Peak Price: \$2,680.21/MWh



Price volatility is the new normal

PJM (ISO) Locational Marginal Prices (LMPs) example



At large scales: University Campus

**72 MW
Peak (UCAP)**

**187
Buildings**

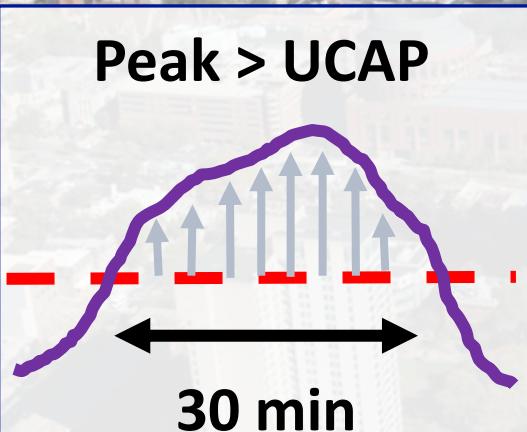
**300,000
SCADA Tags**

**4 Million
Gallons of chilled water (@42F)**

Economic incentives for model based control

**~\$28M
Annual Electricity Bill**

In 2011



**\$720,000
Penalty for 30 minutes**

Why focus on Buildings ?

40%

Portion of global energy use

70%

Portion of electricity consumption in
the United States

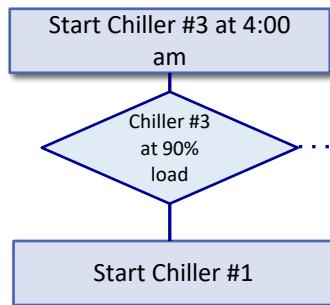
1/3

Portion of global total CO₂ emissions

Model-Based control for buildings

Traditional rule-based building control

- Sequence of operations or planned steps.
- Pre-defined rules set by building engineers.
- Purely reactive.
- Equipment-level controllers (PID) ensure reference tracking.



21

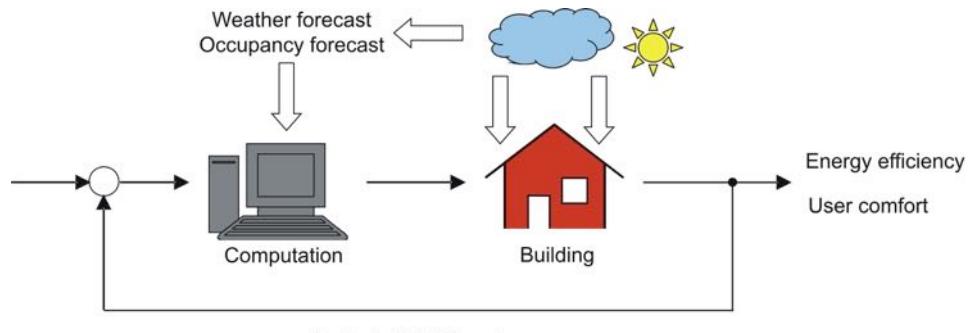
Took 23 min yesterday

22

Took 42 min today
(but price increased !)

Model-based building control

- Model how the building will response to disturbances (weather, occupants etc.)
- Predictive
- Control design:
 - Energy-efficiency
 - Demand flexibility
 - Fault handling
- Okay to use equipment level PID control



Model Predictive Control (MPC)

The control problem in buildings

Integrated control of:

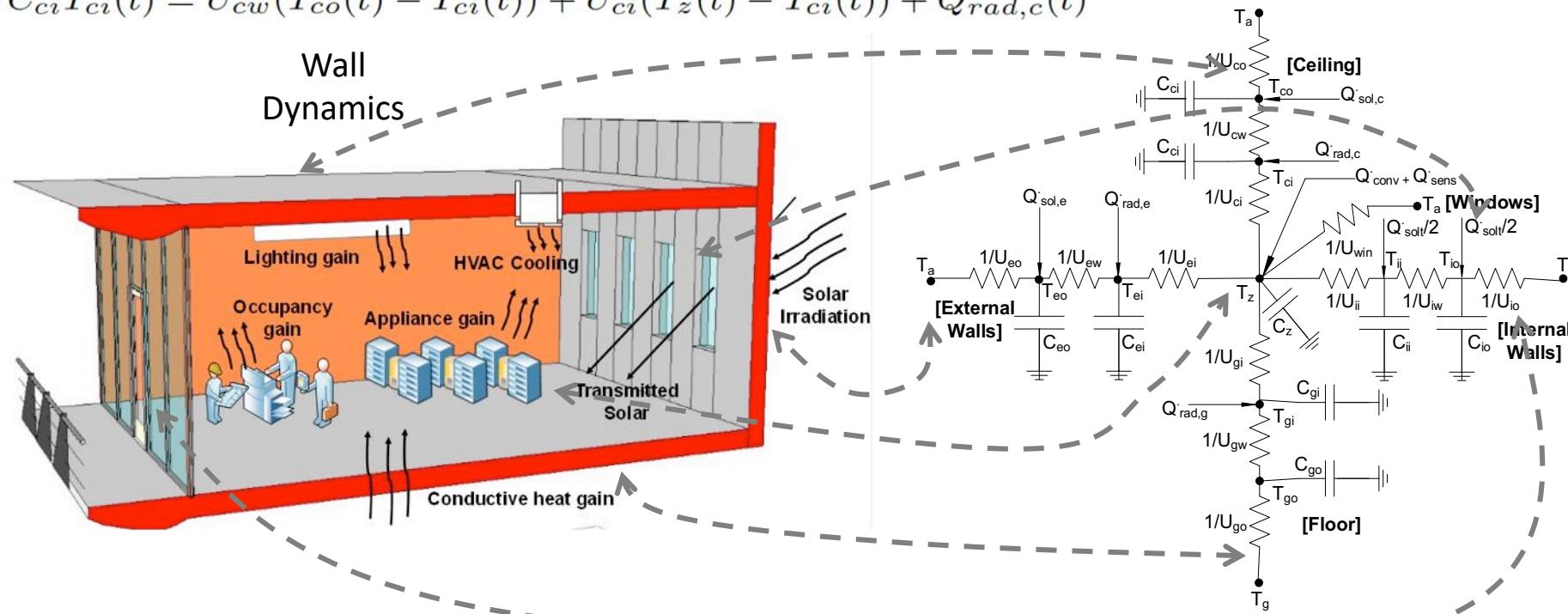
- Heating
- Cooling
- Ventilation
- Lighting
- Blinds



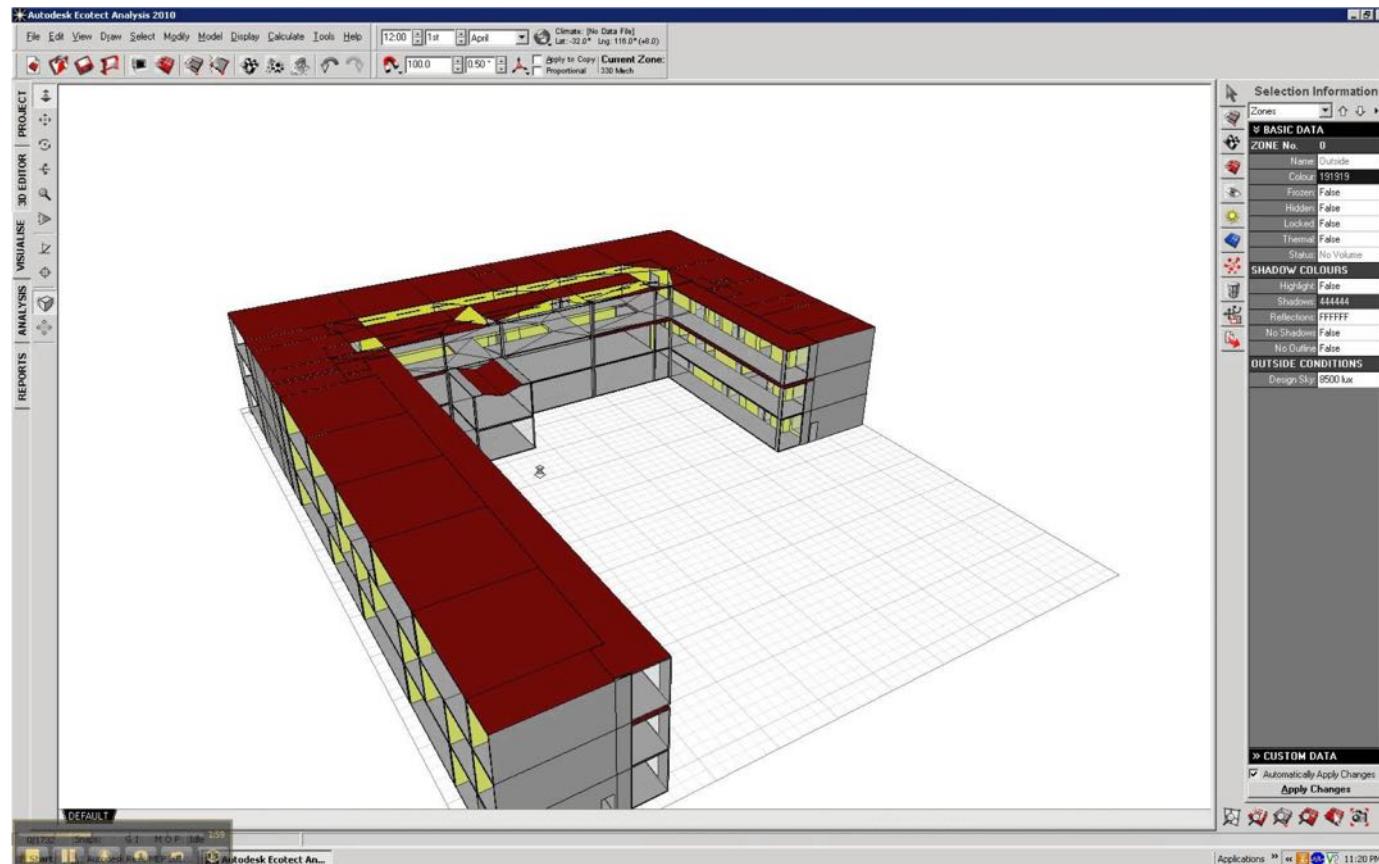
State-space ‘RC’ thermal modeling

$$C_{co} \dot{T}_{co}(t) = U_{co}(T_a(t) - T_{co}(t)) + U_{cw}(T_{ci}(t) - T_{co}(t)) + \dot{Q}_{sol,c}(t)$$

$$C_{ci} \dot{T}_{ci}(t) = U_{cw}(T_{co}(t) - T_{ci}(t)) + U_{ci}(T_z(t) - T_{ci}(t)) + \dot{Q}_{rad,c}(t)$$



Whole building energy simulation

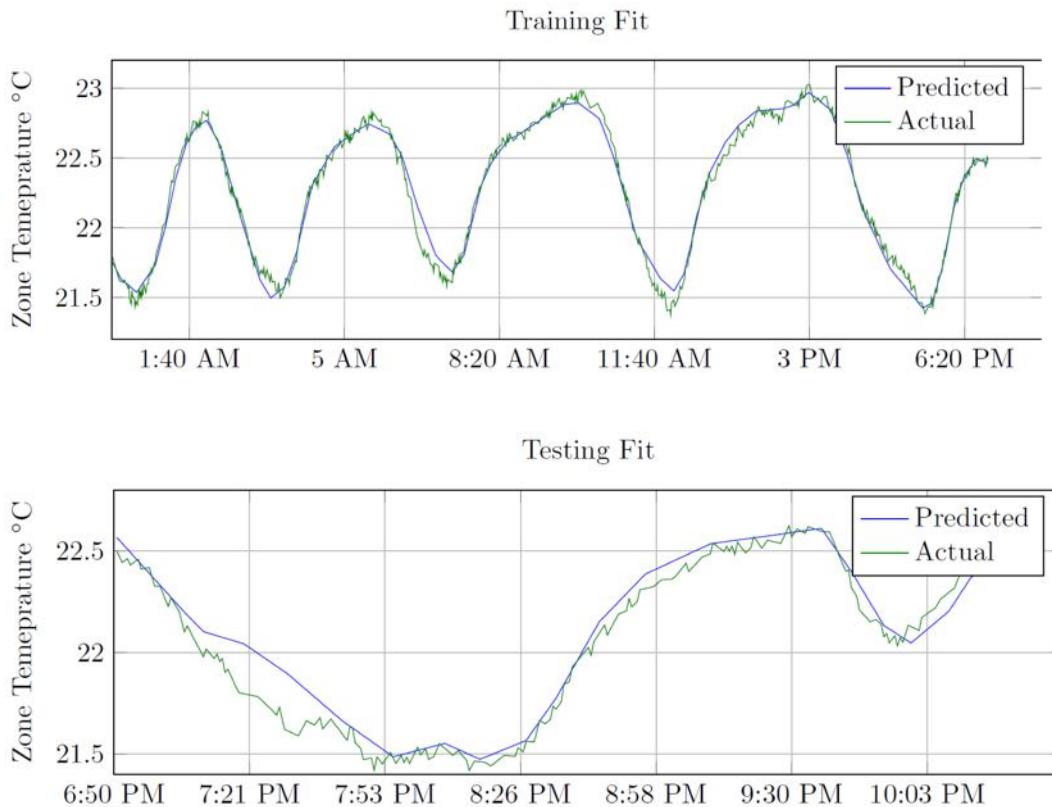


Using EnergyPlus.

Generating input-output data

Modeling a building in MATLAB

Non-linear parameter estimation and model validation



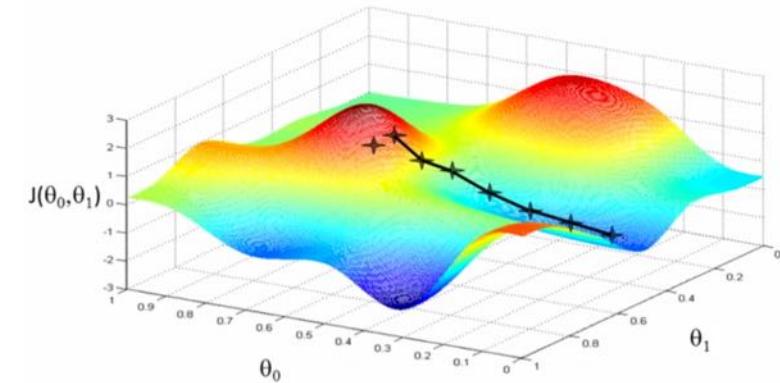
Model Accuracy for Training data

RMSE: 0.062 °C
R2: 0.983

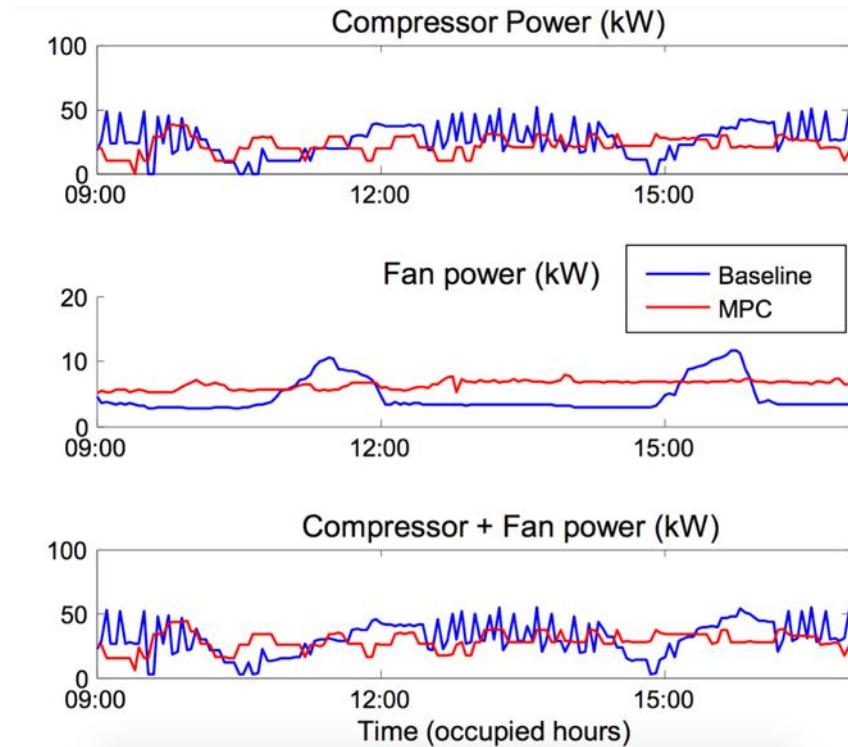
Baseline

Model Accuracy for Test Data

RMSE: 0.091 °C
R2: 0.948



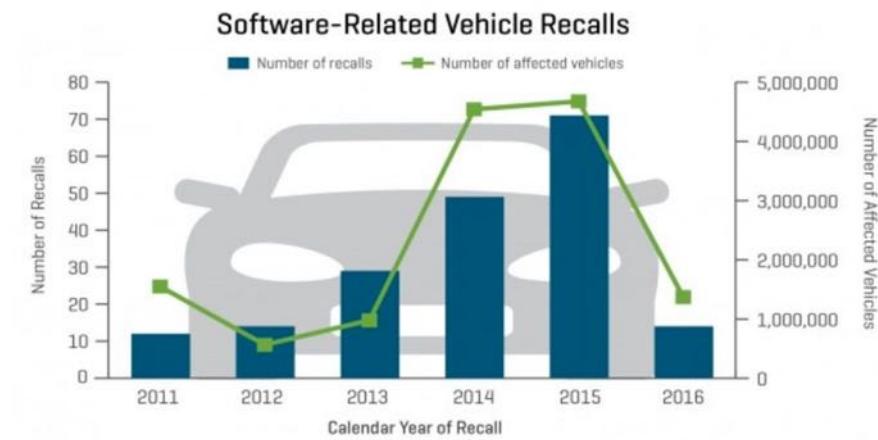
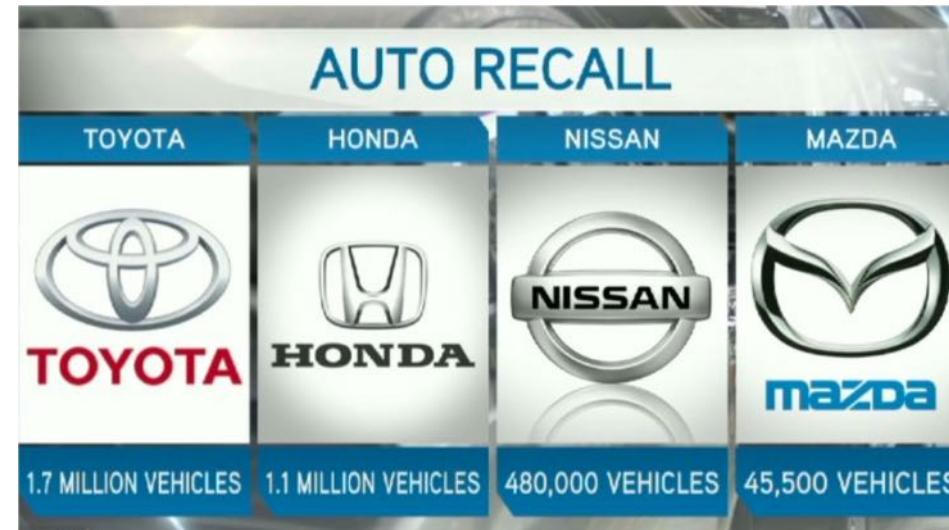
Predictive control





Medical CPS Module

Software related vehicle recalls



IMPLANTABLE DEVICES RECALL

- Over 600,000 cardiac medical devices recalled from 1990-2000
 - 40% of which were due to software issues
- 2008-12: **15% of all** the medical device recalls due to software



Implantable Pacemaker

Principles of modeling for CPS – Fall 2018



Implantable Cardioverter-Defibrillator (ICD)

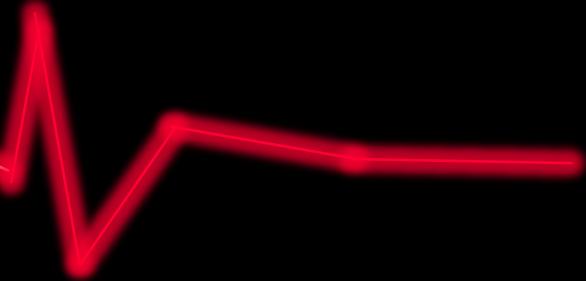
Madhur Behl - madhur.behl@virginia.edu

THE HEART



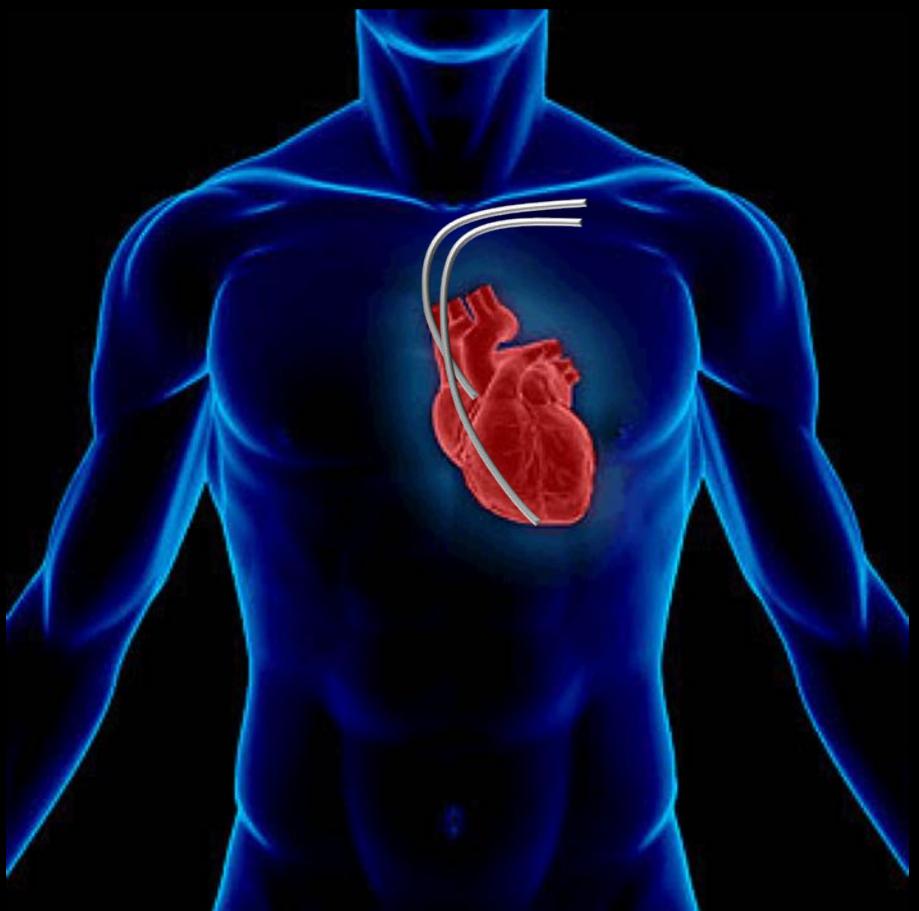
- Muscle contraction triggered by **electrical signals**

BRADYCARDIA



- Slow **generation** and **conduction** of electrical signals
- Slow heart rate
- Symptom: fainting, dizziness
- Could lead to heart attack

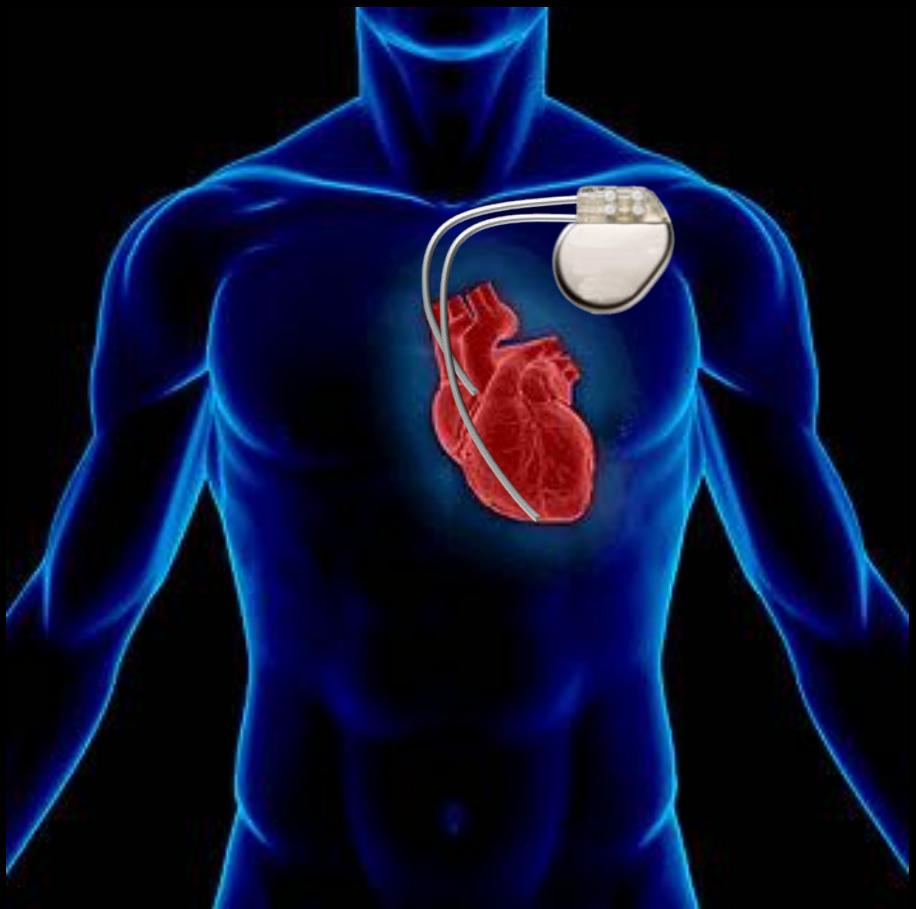
IMPLANTABLE PACEMAKER



-  No leads in heart chambers

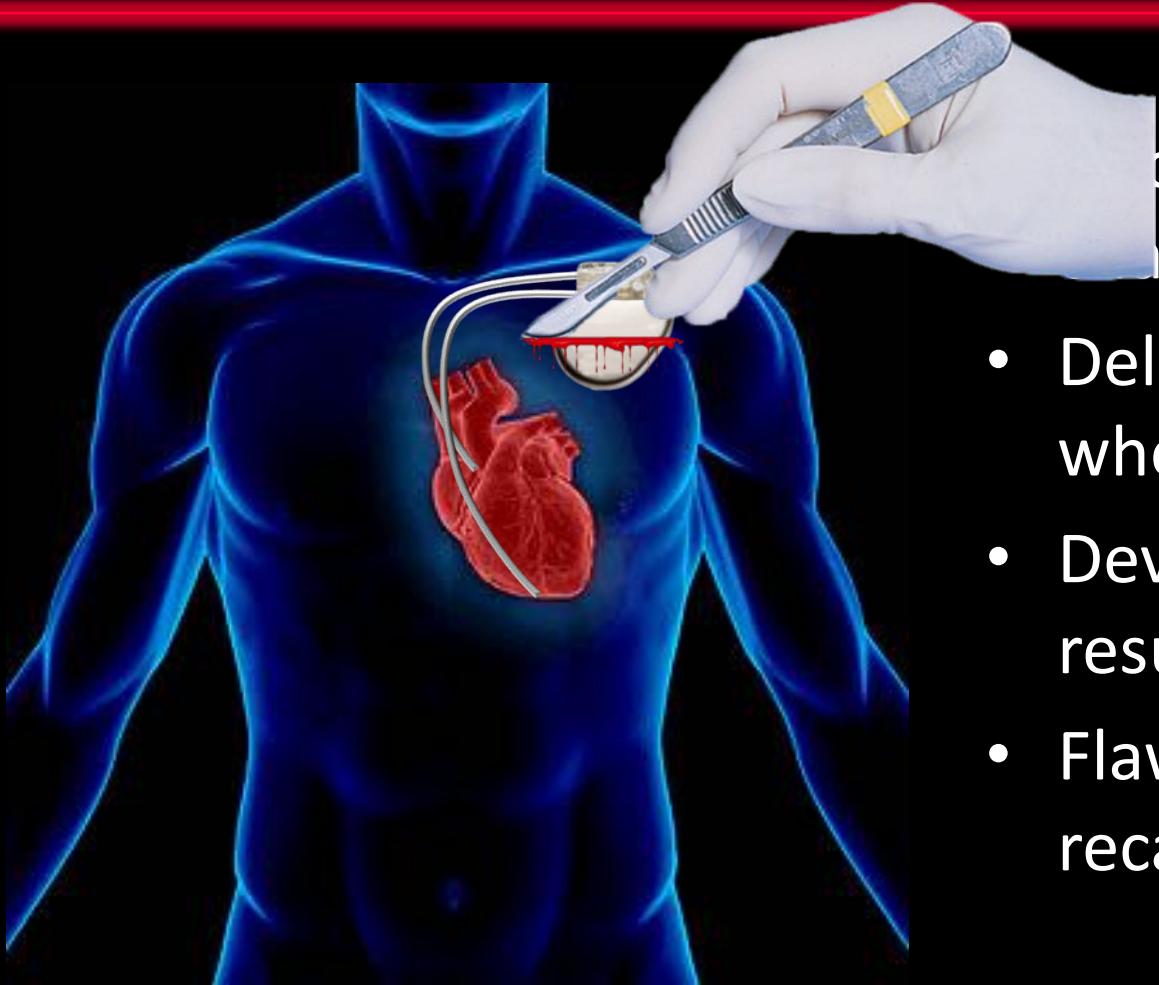


IMPLANTABLE PACEMAKER



- Two leads in heart chambers
- Deliver electrical signals when heart rate is low

IMPLANTABLE PACEMAKER



Two leads in heart
chambers

- Deliver electrical signals when heart rate is low
- Device malfunction may result in **injury or death**
- Flawed devices are recalled

CHALLENGES



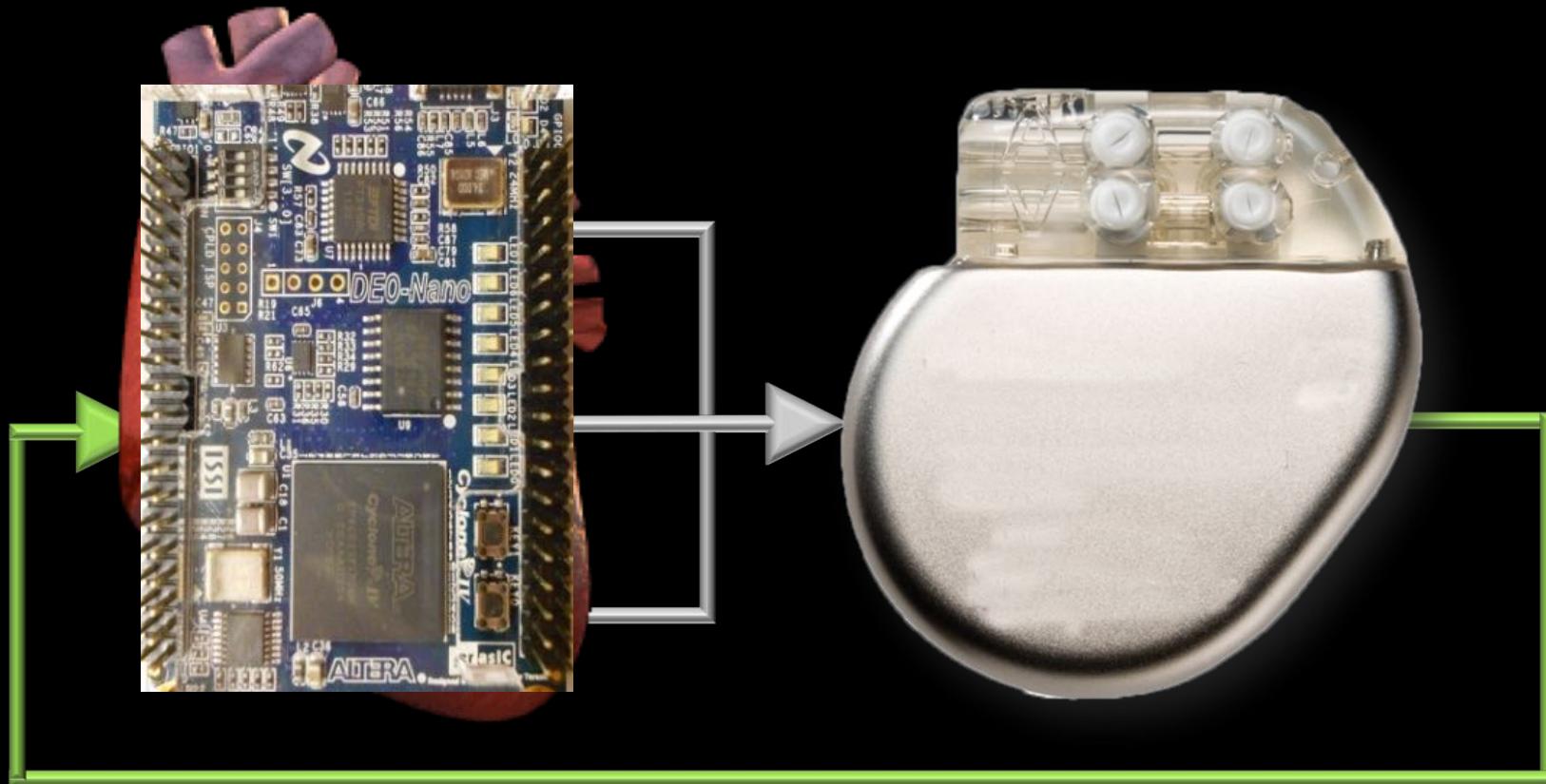
Pacemaker

- Autonomous device with minimum human interaction
- Limited diagnostic/therapy capability
- Its safety must be evaluated within its environment

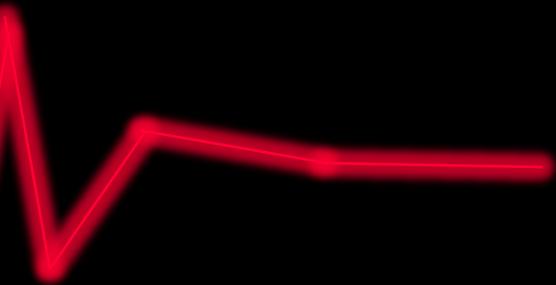
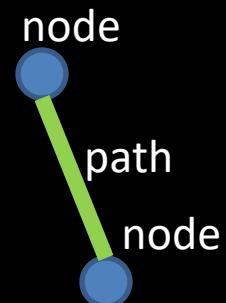
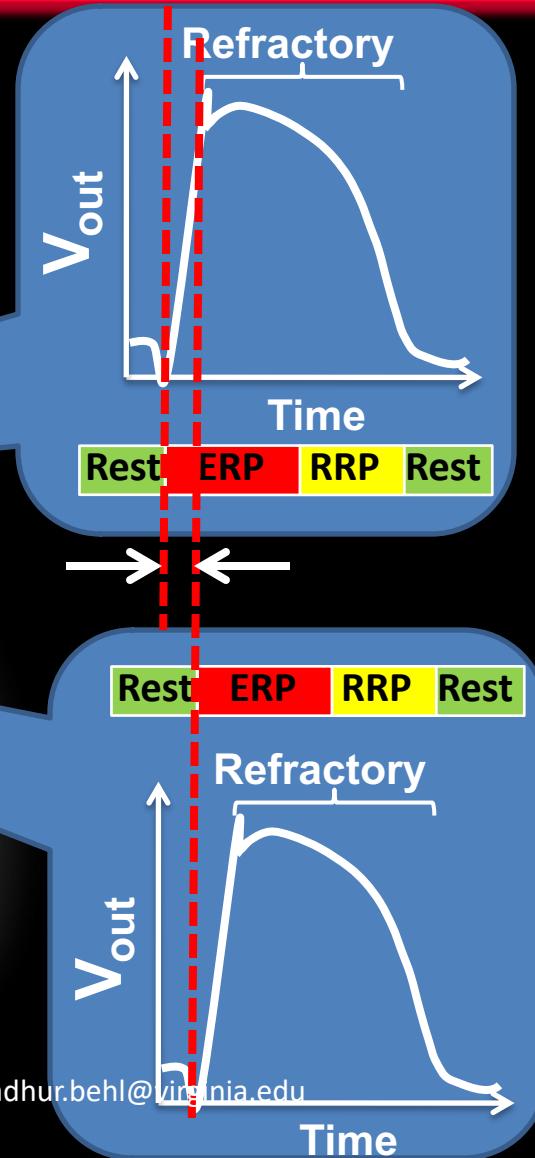
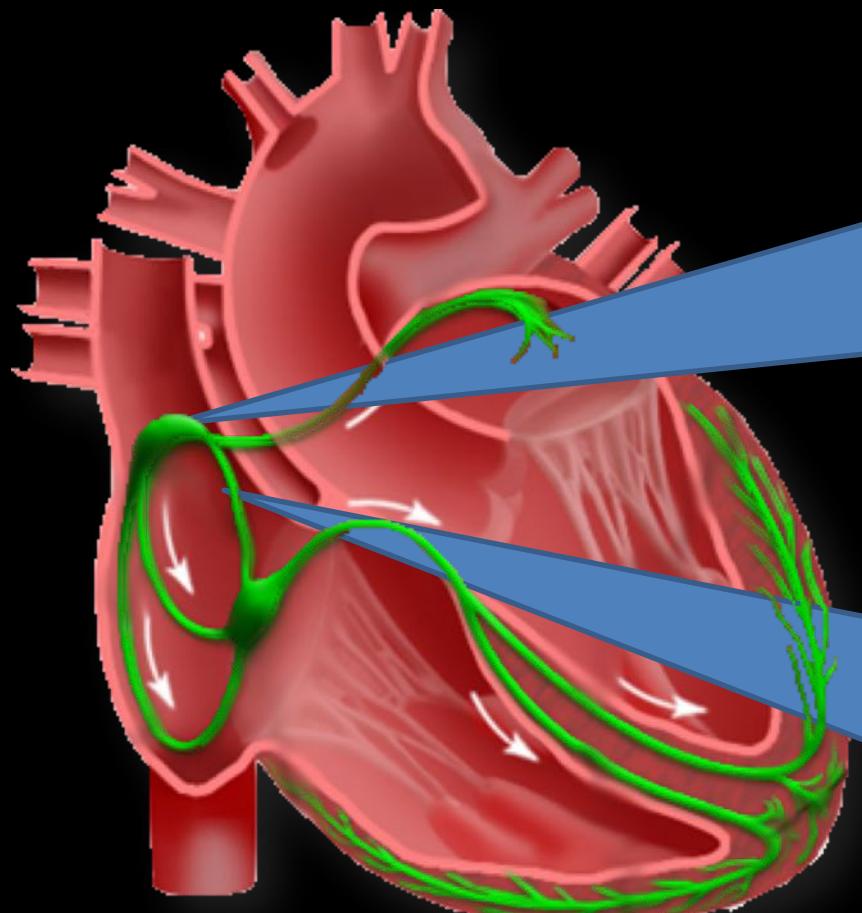
The physical plant:

- Complex dynamics of the heart
- Interaction between the heart and the body
- Domain knowledge

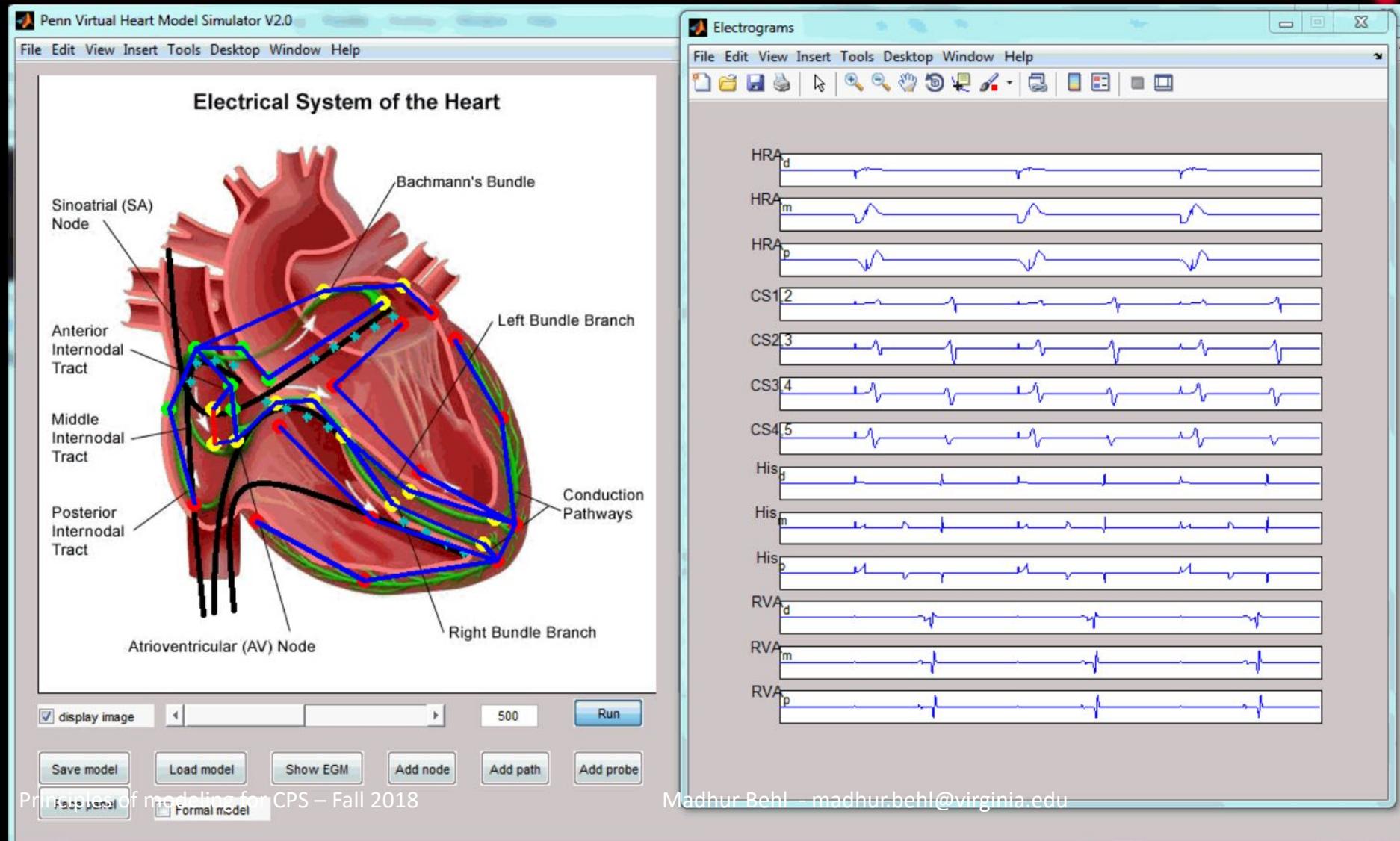
CLOSED-LOOP EVALUATION



HEART MODELING

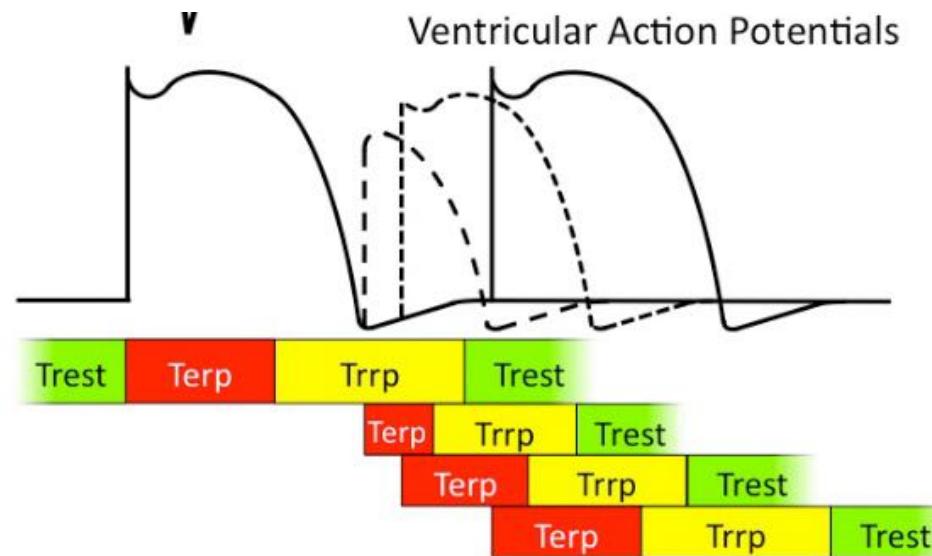


CLOSED-LOOP HEART MODELING

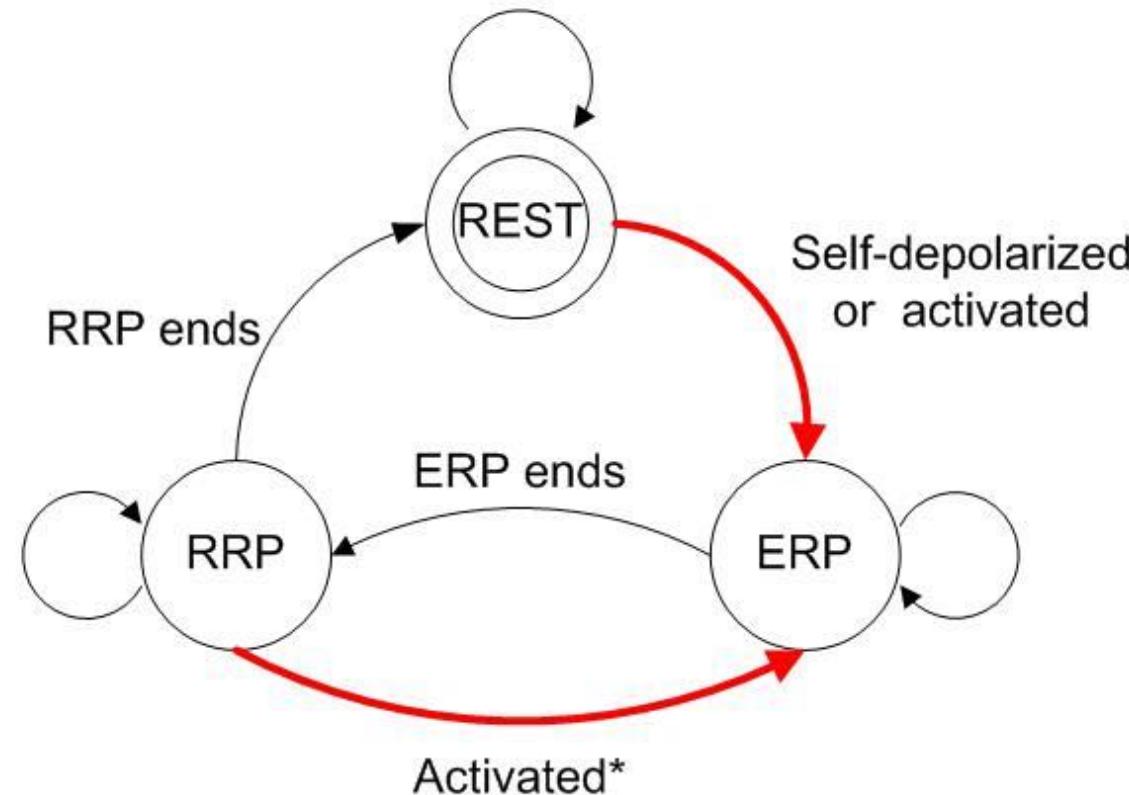


Node Automaton

- Divide refractory period into time periods
- Model refractory properties as timers using timed automata.
- These time periods can be measured during EP study

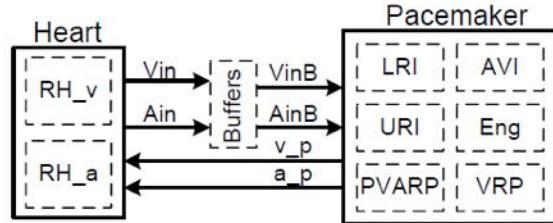


Node Automaton

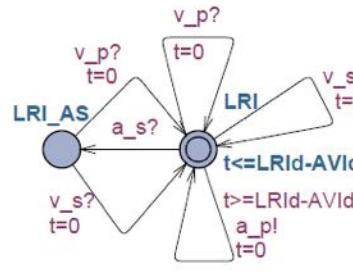


* With changes in ERP and conduction speed of paths connecting to the node

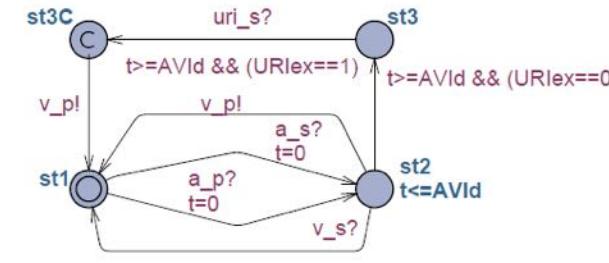
The UPPAAL model of the closed-loop system



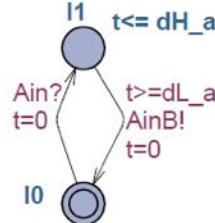
(a) Interaction between the pacemaker and heart



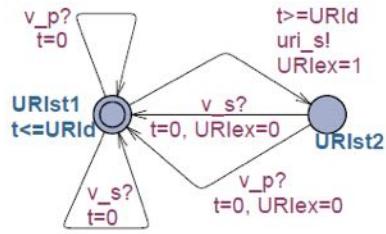
(b) LRI component



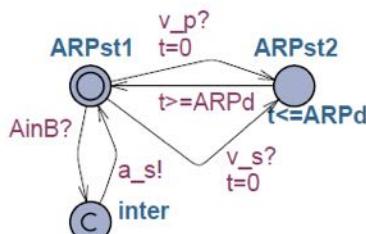
(c) AVI component



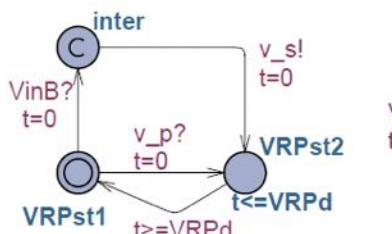
(d) Atrial Buffer



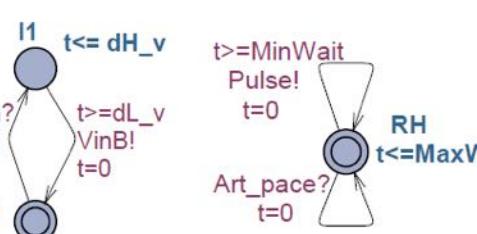
(e) URI component



(f) PVARP component



(g) VRP component



(h) Vent. Buffer

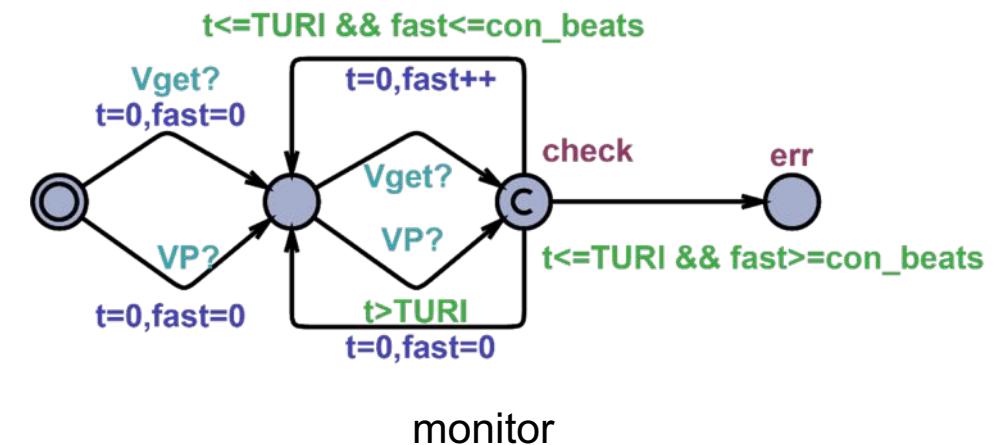
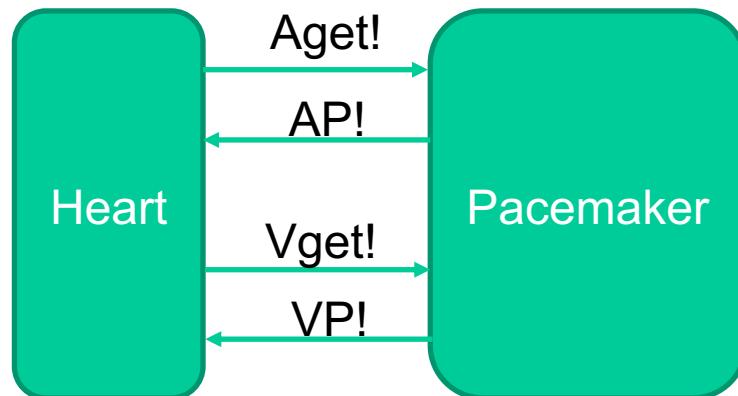


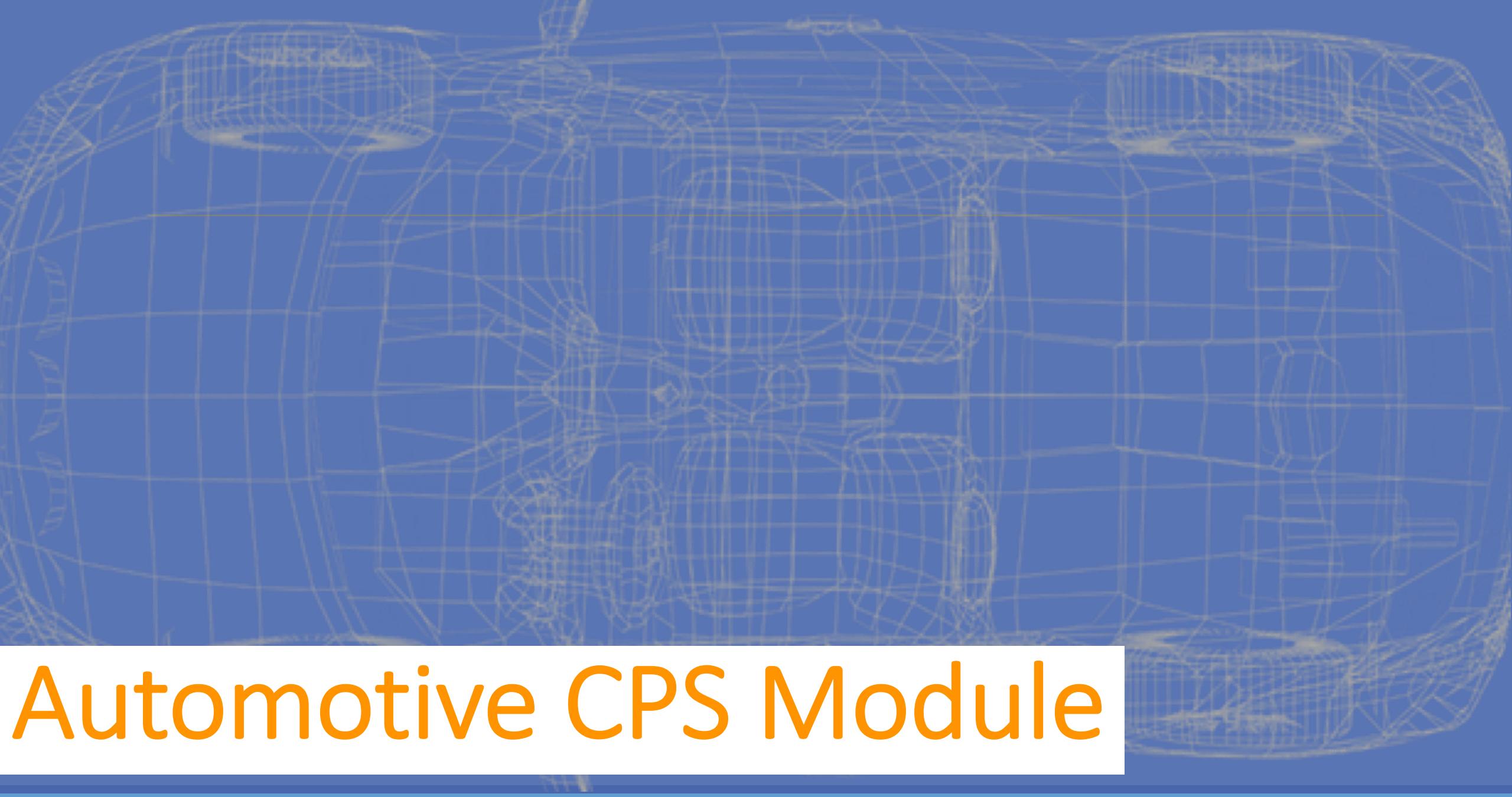
Model checking – Counter example guided.

Safety property

Ventricular rate should not be equal or above the upper rate limit for more than 30 beats

$A[] \neg \text{monitor}.err$





Automotive CPS Module

Localization and Mapping

Where am I ?

Scene Understanding

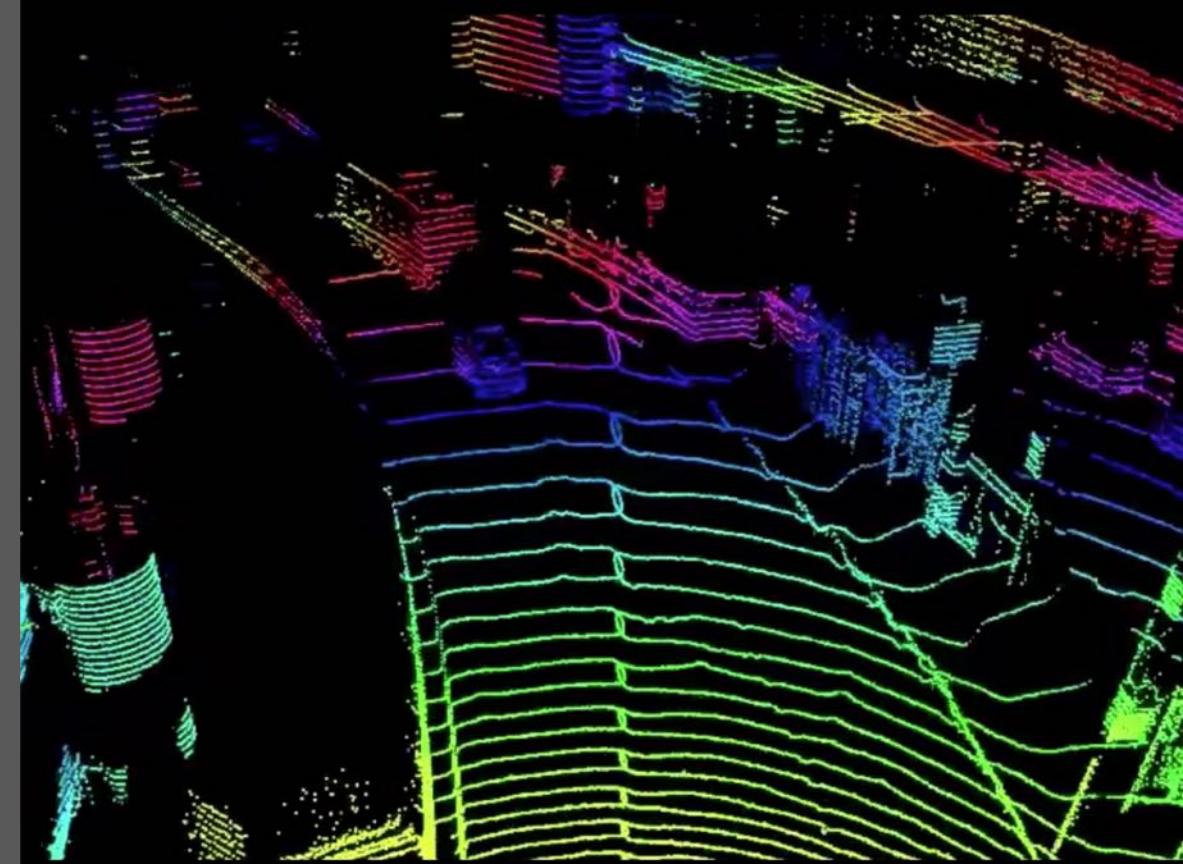
Where/who/what/why of everyone/everything else ?

Trajectory Planning and Control

Where should I go next ?
How do I steer and accelerate ?

Human Interaction

How do I convey my intent to the passenger and everyone else ?



Localization and Mapping

Where am I ?

Deep Learning

Scene Understanding

Where/who/what/why of everyone/everything else ?

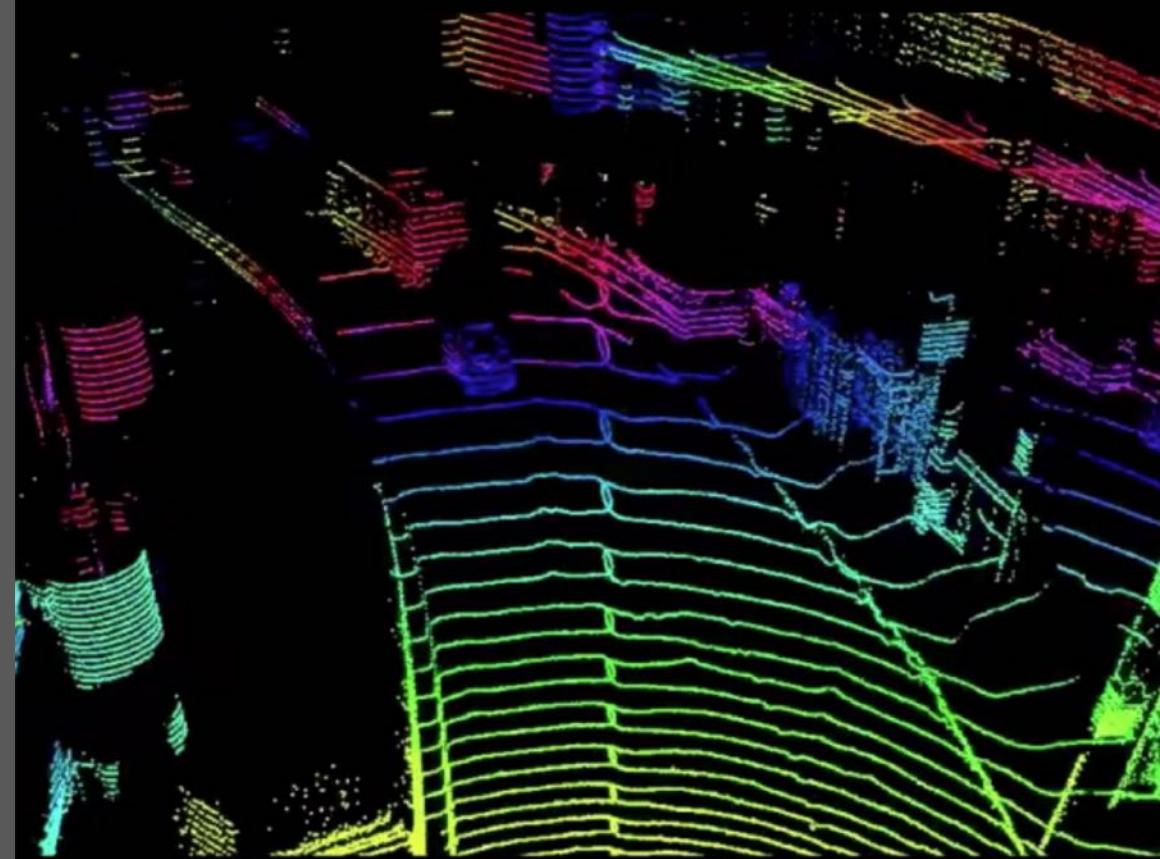
Trajectory Planning and Control

Where should I go next ?

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Human Interaction

How do I convey my intent to the passenger and everyone else ?



Localization and Mapping

Where am I ?

Deep Neural Networks

Scene Understanding

Where/who/what/why of everyone/everything else ?

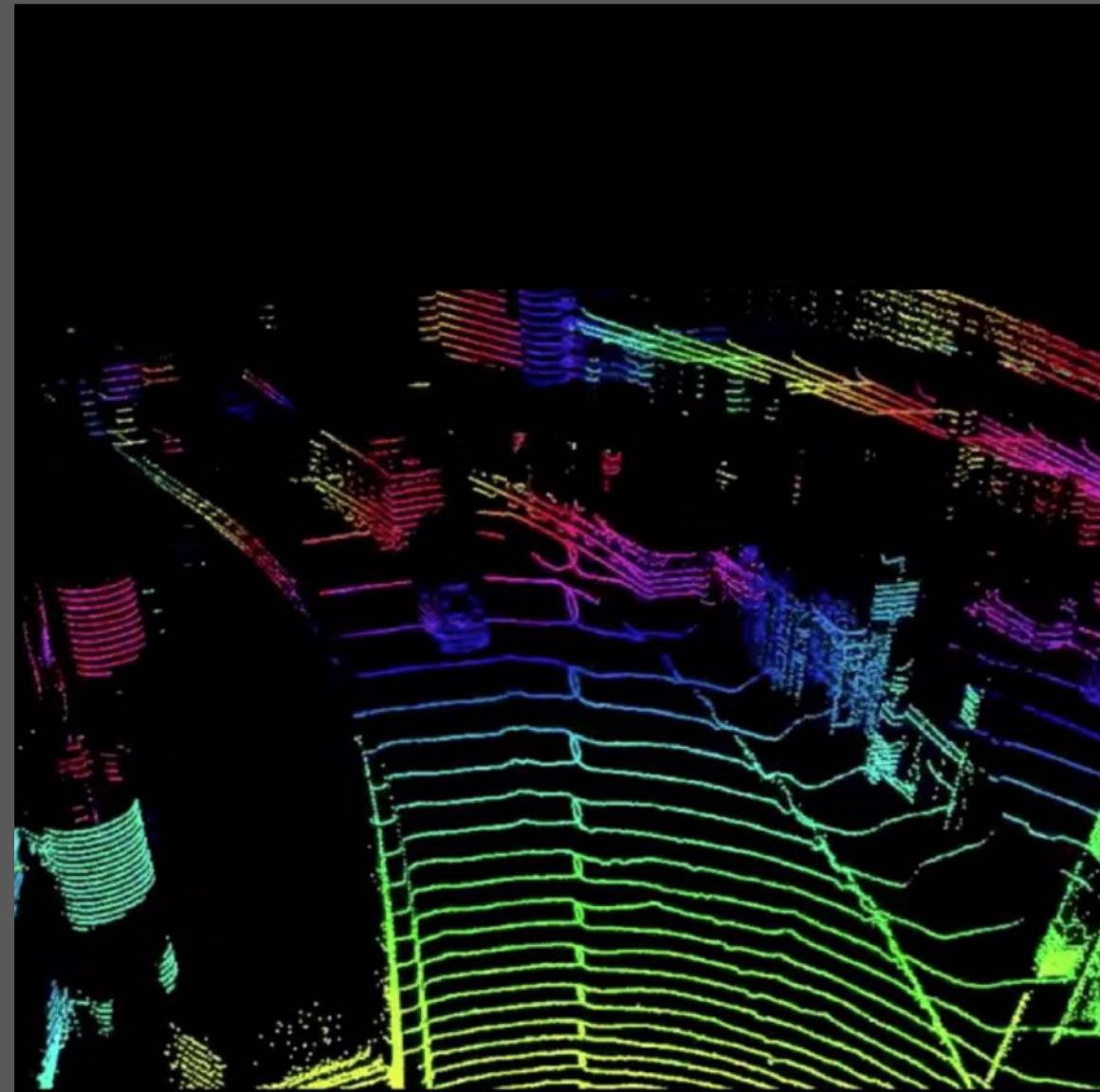
Trajectory Planning and Control

Where should I go next ?

How do I steer and accelerate ?

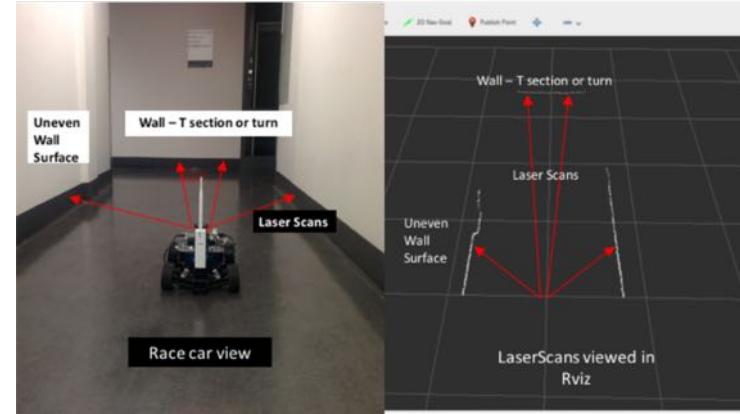
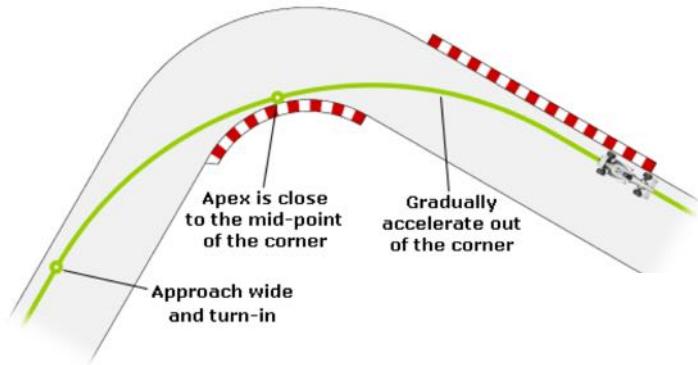
Human Interaction

How do I convey my intent to the passenger and everyone else ?



Perception. Planning. Control

Making sense of the surroundings

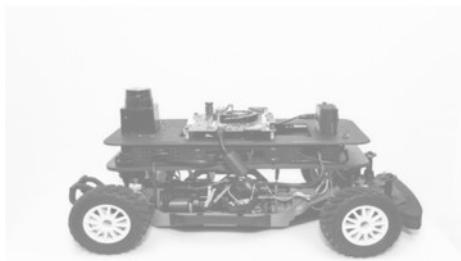
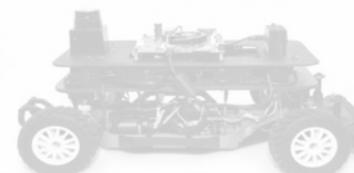
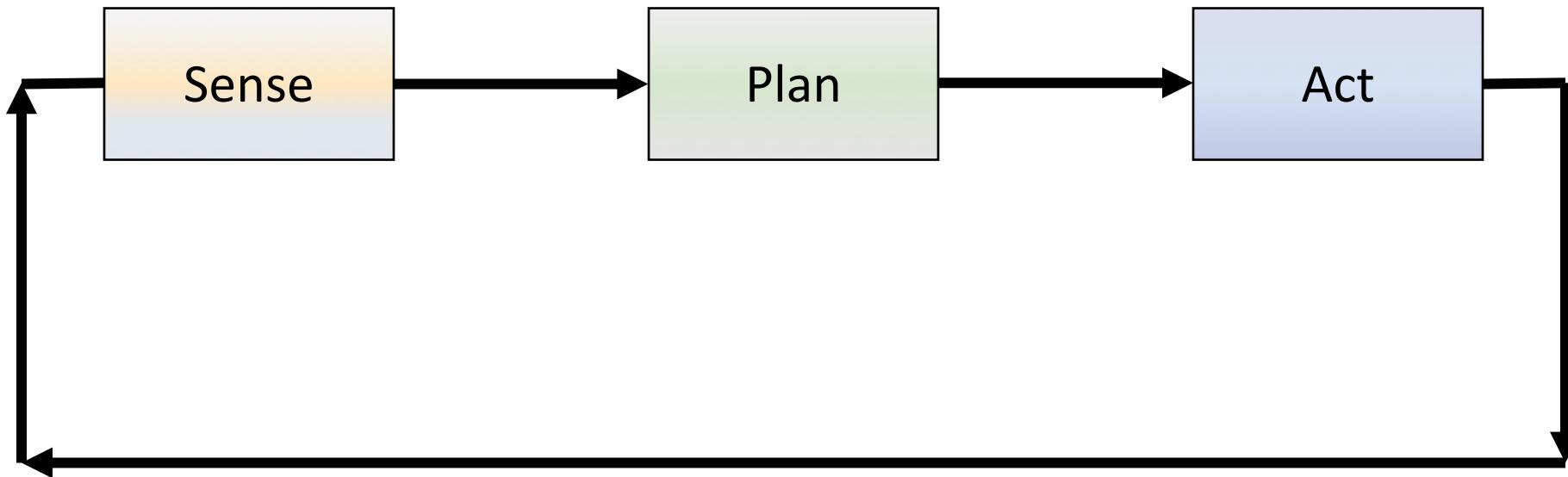


Planning the desired trajectory

Controlling the car to follow the planned path



Closing the loop



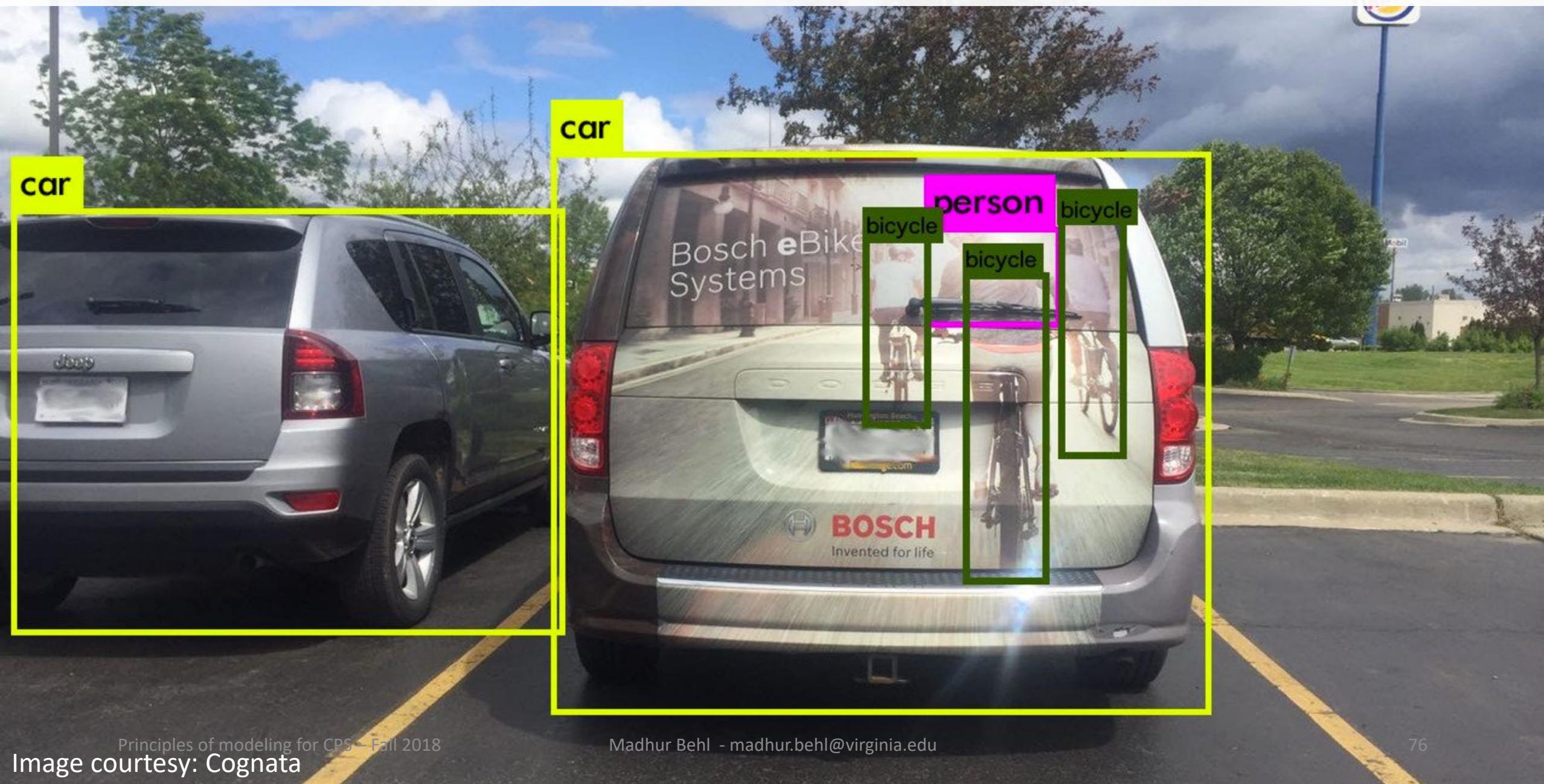
End-to-End Deep Learning for Self Driving Cars

- NVIDIA

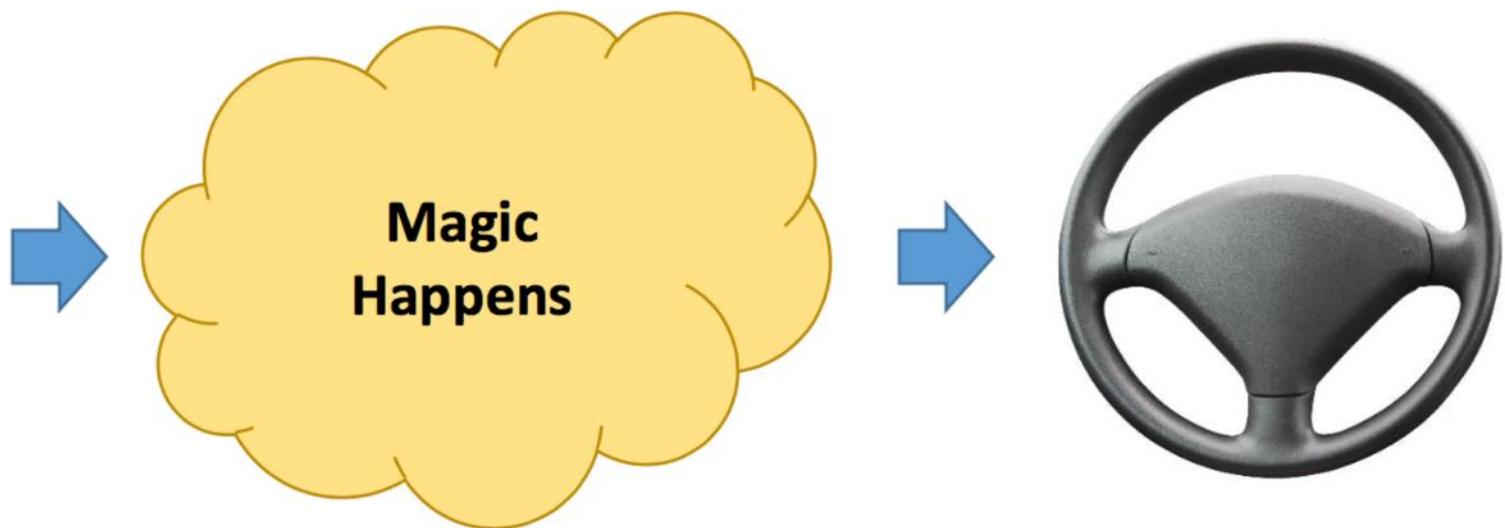


Machine intelligence is largely about training data.

When's a pedestrian not a pedestrian? When it's a decal.



Autonomous Driving: End-to-End



Autonomous Driving: End-to-End

End to End Learning for Self-Driving Cars

Mariusz Bojarski
NVIDIA Corporation
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Davide Del Testa
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Daniel Dworakowski
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Beat Flepp
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Prasoon Goyal
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Mathew Monfort
NVIDIA Corporation
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Urs Muller
NVIDIA Corporation
Holmdel, NJ 07735

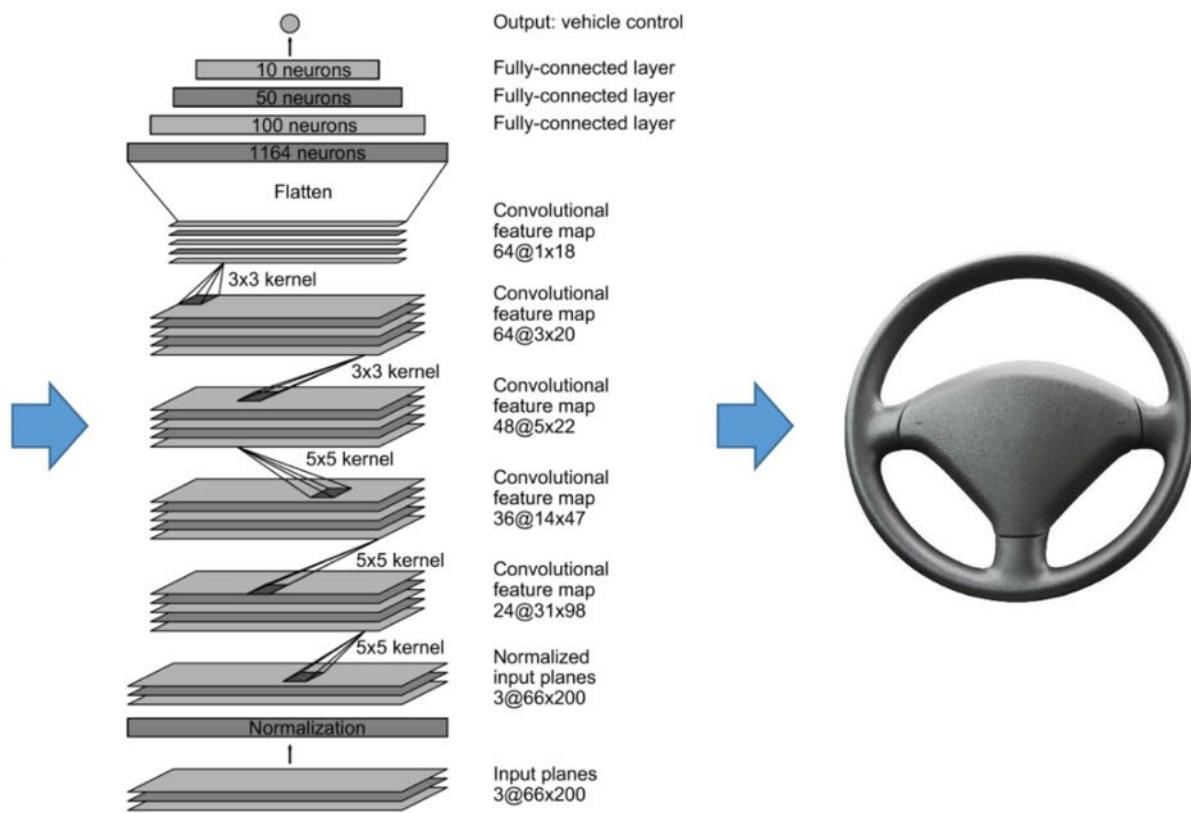
Jiakai Zhang
NVIDIA Corporation
Holmdel, NJ 07735

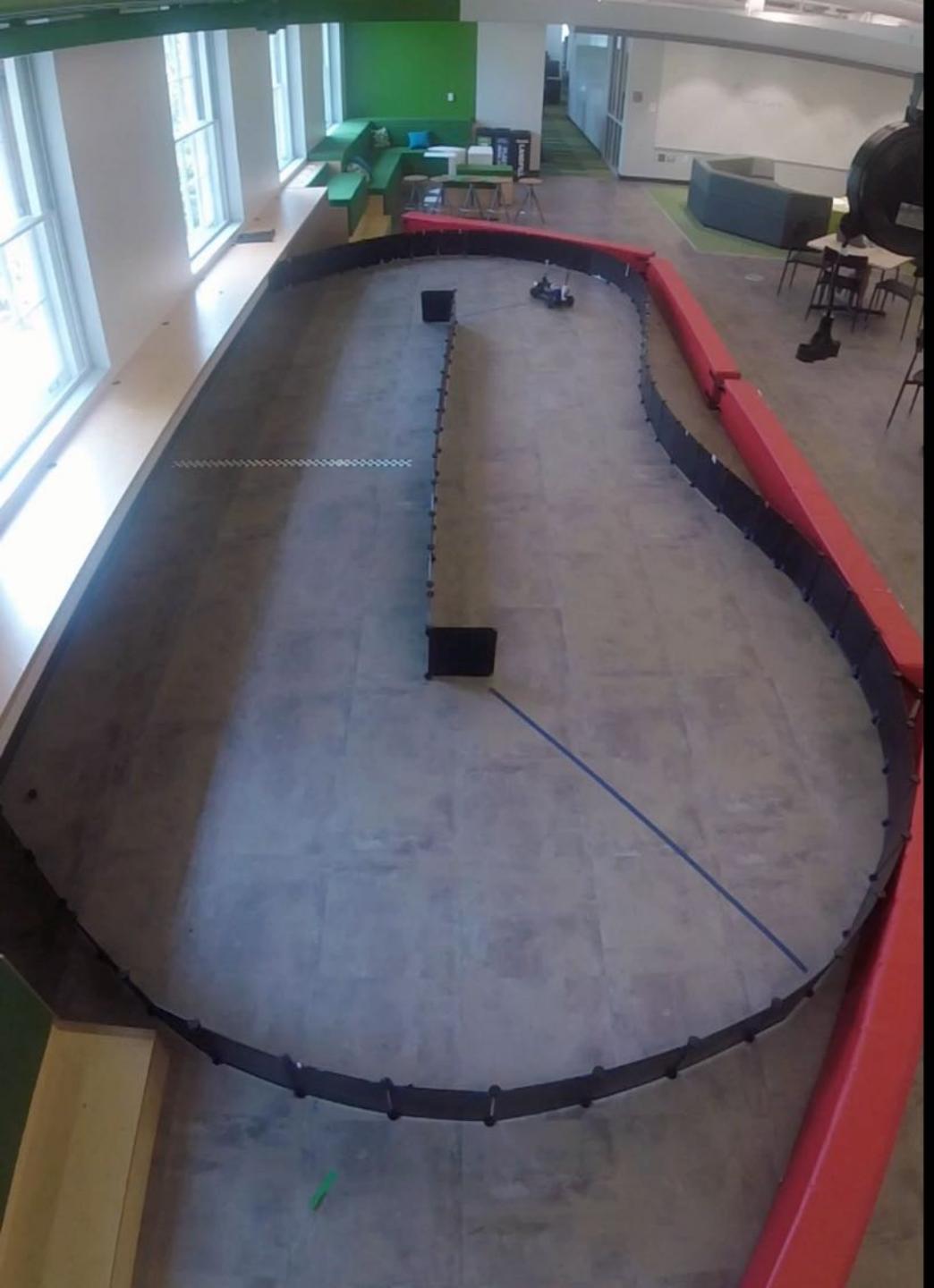
Xin Zhang
NVIDIA Corporation
Holmdel, NJ 07735

Jake Zhao
NVIDIA Corporation
Holmdel, NJ 07735

Karol Zieba
NVIDIA Corporation
Holmdel, NJ 07735

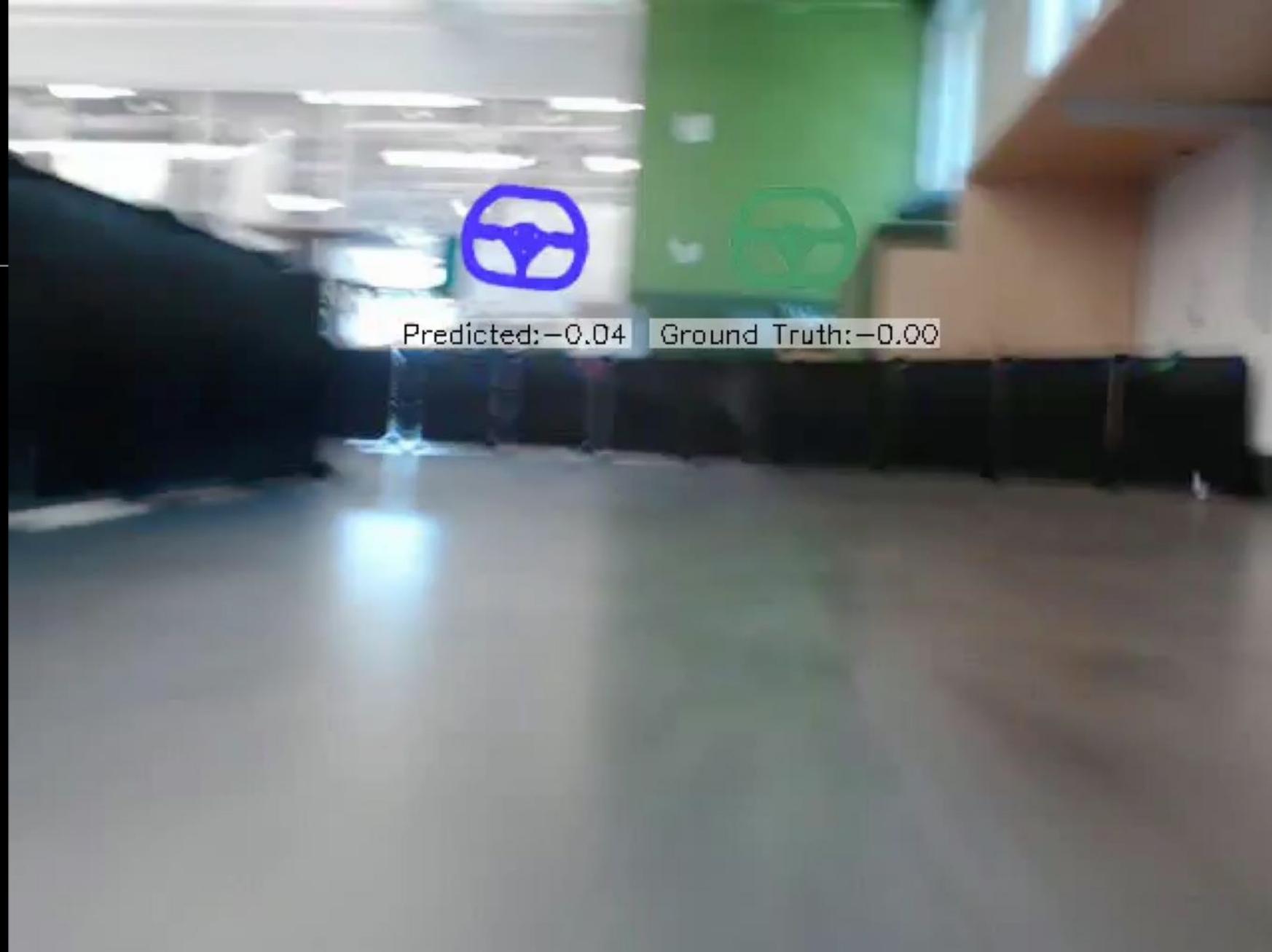
Autonomous Driving: End-to-End





F1/10 FPV Driving





what is this course about ?

Principles of Modeling for Cyber-Physical Systems

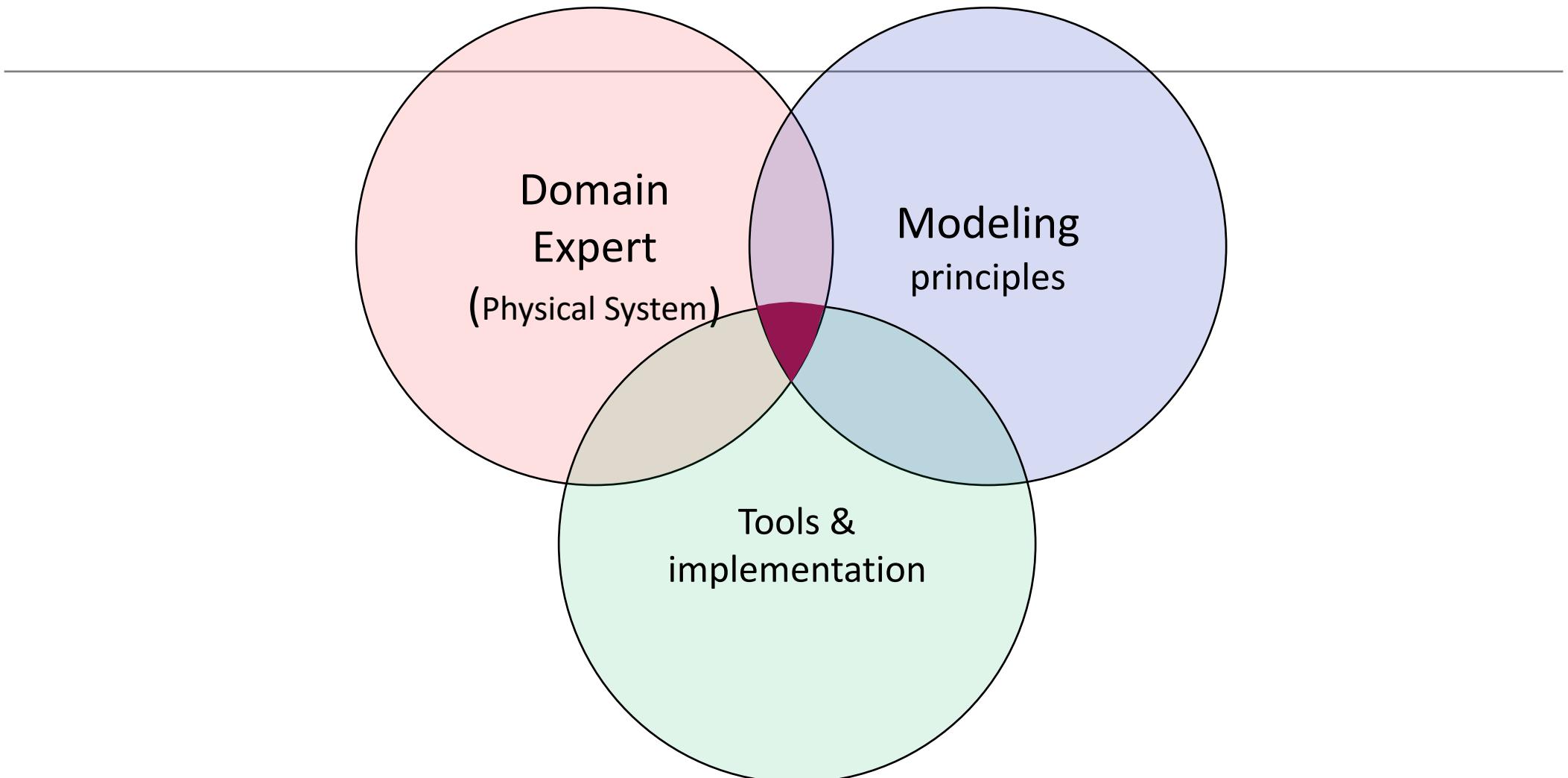
Lets break it down..

1. What are Cyber-Physical Systems ?
2. What do you really mean by modeling ?
3. What principles am I going to learn about ?

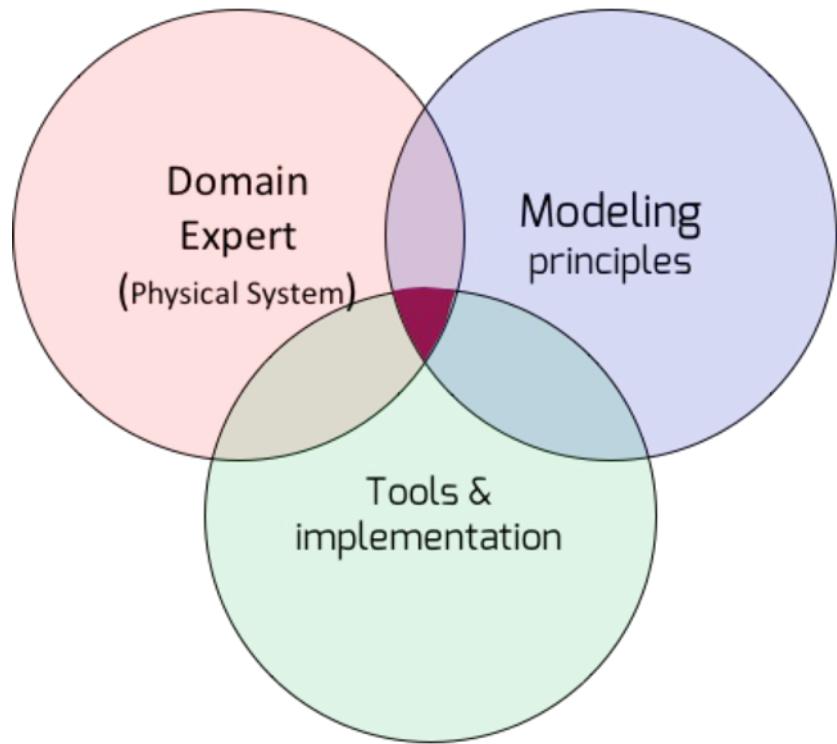
This course: Modeling principles

- Modeling for predictive control.
- Parameter estimation.
 - Linear and non-linear
- Model checking
- Model validation
- Model selection
 - Model abstraction/reduced order modeling
- End-to-end learning

This course: Learning objectives



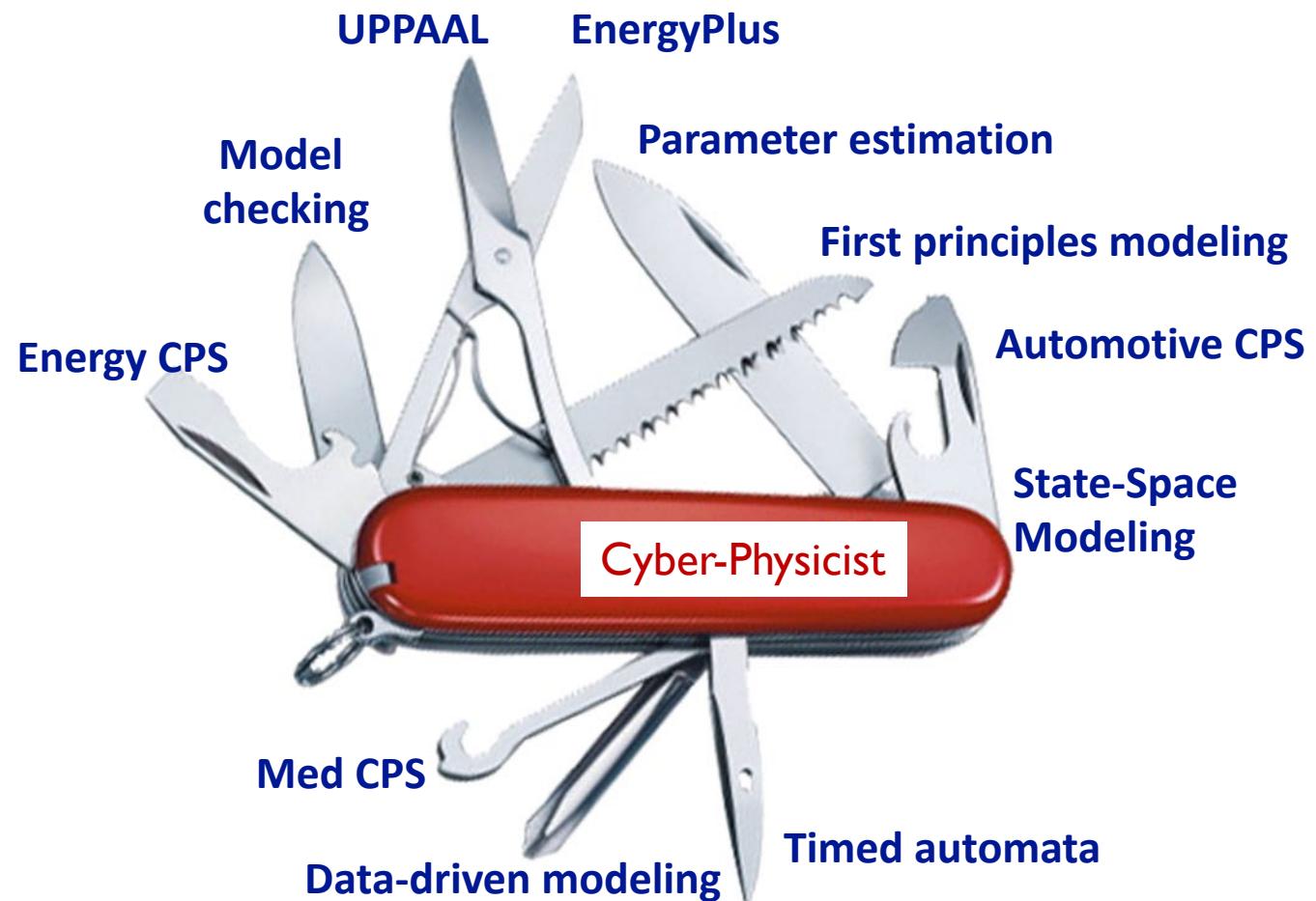
This course: Learning objectives



The future belongs to those who learn more skills and combine them in creative ways.

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This course: Becoming a Cyber-Physicist



Next lecture:

- How to predict the future..
 - State-space modeling using first principles.
 - Mechanical, electrical, thermal systems
 - ODEs and elements of white box modeling