Principles of Modeling for Cyber-Physical Systems

Fall 2018

CS 6501-003 / SYS 6581-004/600

Madhur Behl

Computer Science

Systems and Information Engineering

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

This lecture

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

Course Logistics

- **Timings:** Tue & Thu 2:00pm – 3:15pm,
- **Location:** Olsson Hall 018

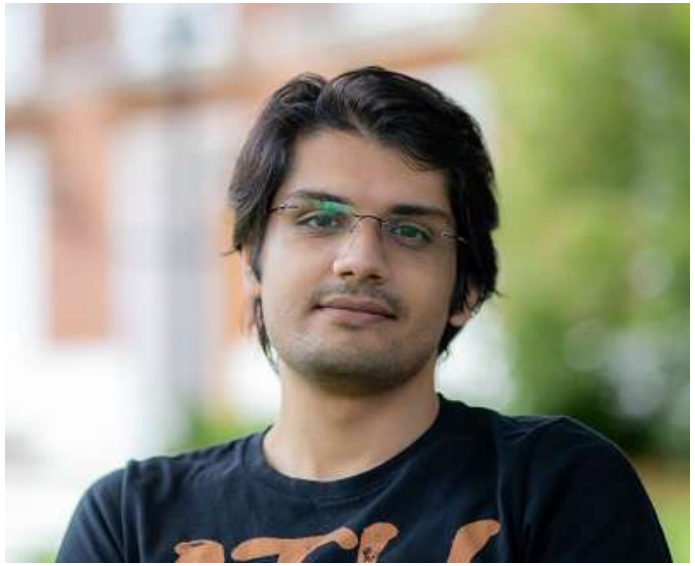
- **Course website:** https://linklab-uva.github.io/modeling_cps/
- All lectures notes/slides/assignments/videos will be posted on this website.

- **Piazza:** https://piazza.com/virginia/fall2019/modelingcpsfall2019/home

- **Prerequisites (must have):**
  - Some familiarity with Matlab / Simulink.
  - Some programming experience, Python is a plus.
  - Mathematical maturity (differential equations, matrix operations, some calculus, probability distributions)
- **Prerequisites (good to have):**
  - Machine learning
  - Temporal logic
  - Model predictive control

Teaching Assistants

Siavash Yousefi Jordehi



sy3fw@virginia.edu

Systems Engineering, PhD

Jiechao Gao

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Computer Science, PhD

Office Hours: TBA

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 (posted on UVACollab/Website) 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. 25% grade lost for each additional late day.

- Abide by the UVA honor system. Absolutely no code/solution sharing !

Office Hours

- Timings: Monday 2-3pm, or by appointment.
- Location: Link Lab Room 265 [Olsson Hall 2nd floor]
- Available by appointment outside of the listed hours:
  - To discuss course assignments or lectures.
  - Research opportunities.
- Live streamed office hours will be held for online CGEP students.

Your responsibilities.

- Attend the lectures (in-person for on-grounds students)

- Check Piazza and the Course website for announcements, and assignments.

- Ask questions !
  - Ask, disagree, debate..

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 ?

Cyber-Physical Systems

Deeply integrating

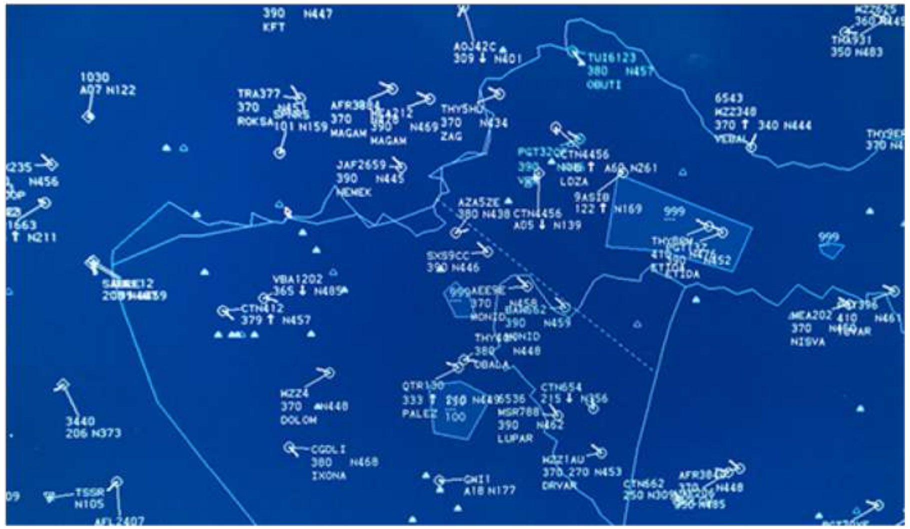
computation, communication, and control

into **physical systems**

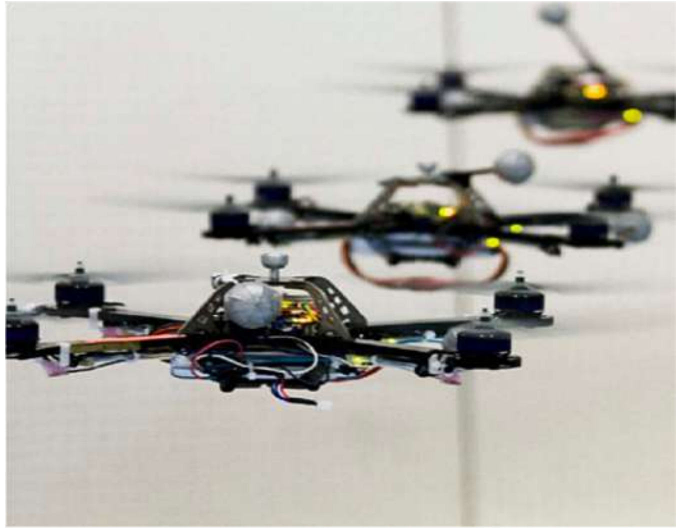
- Physical = some tangible, physical device or system + environment
- Cyber = computational + communicational

Application domains: Transportation

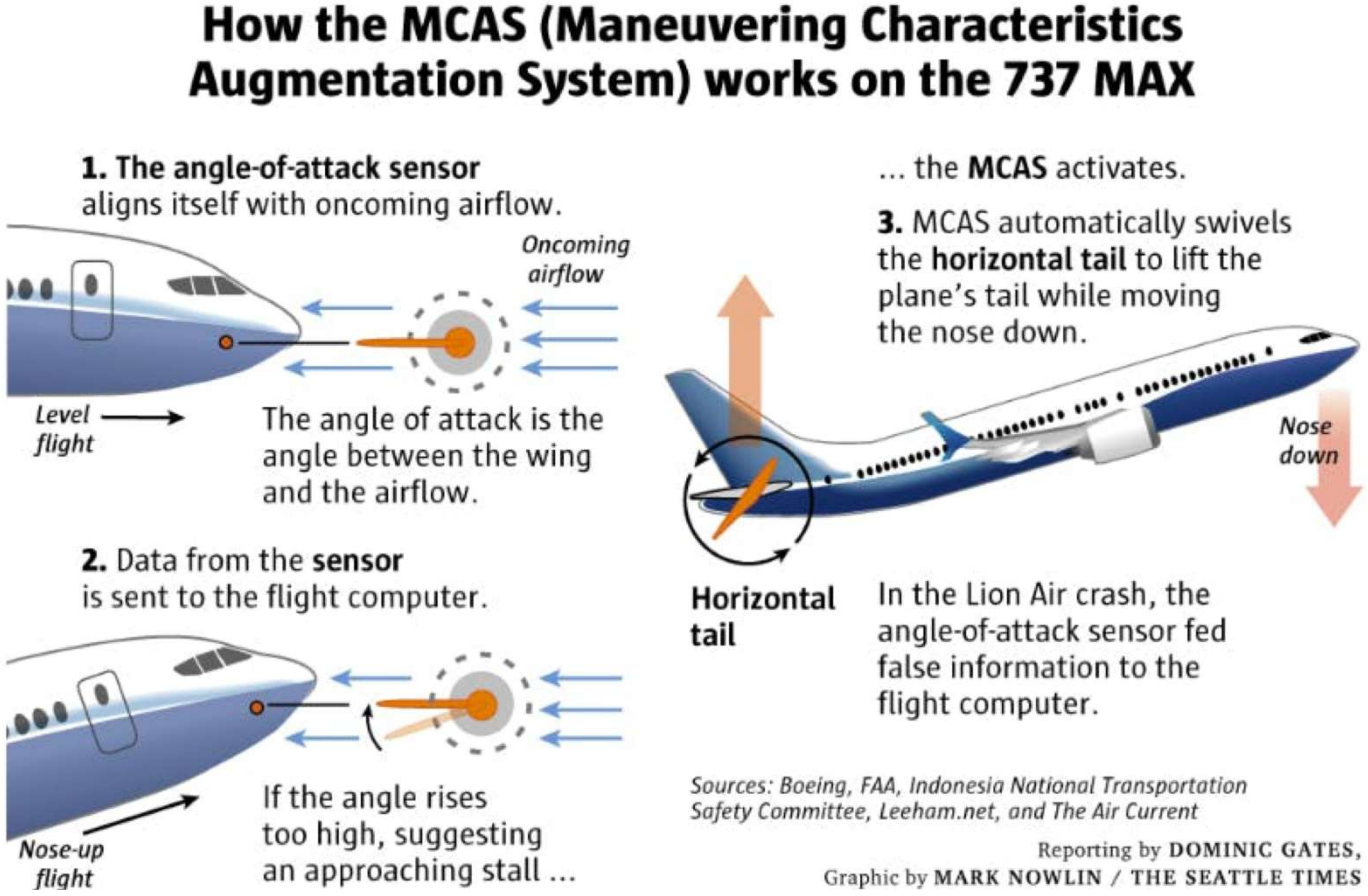
Faster, safer, more energy-efficient air travel



Improved use of airspace



Autonomous unmanned drones


How the MCAS (Maneuvering Characteristics Augmentation System) works on the 737 MAX
1. The angle-of-attack sensor aligns itself with oncoming airflow.
Oncoming airflow
Level flight
The angle of attack is the angle between the wing and the airflow.
2. Data from the sensor is sent to the flight computer.
Nose-up flight
If the angle rises too high, suggesting an approaching stall ...
... the MCAS activates.
3. MCAS automatically swivels the horizontal tail to lift the plane's tail while moving the nose down.
Nose down
Horizontal tail
In the Lion Air crash, the angle-of-attack sensor fed false information to the flight computer.
Sources: Boeing, FAA, Indonesia National Transportation Safety Committee, Leeham.net, and The Air Current
Reporting by DOMINIC GATES,
Graphic by MARK NOWLIN / THE SEATTLE TIMES

Unique requirements for safeguarding aircraft

Cyber-physical systems are ones that integrate physical components through computation and networking, and they present unique challenges and opportunities for cyber defense.

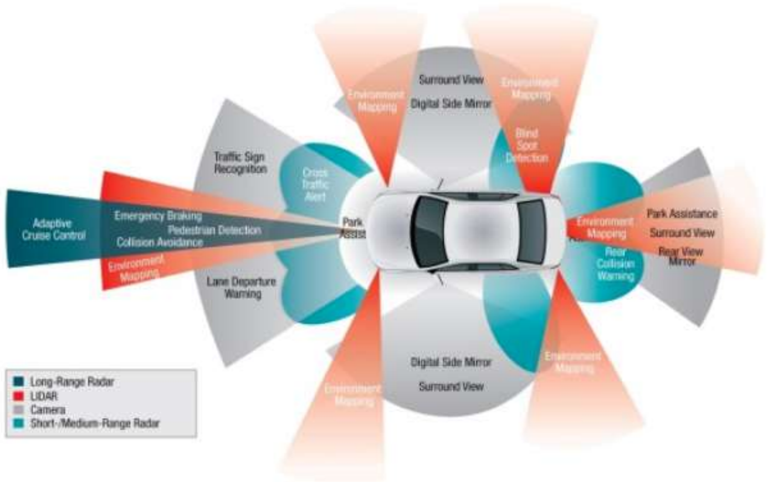
Boeing rotorcraft test pilot Roger Hehr (left) reviews security features following a successful High-Assurance Cyber Military Systems flight test on the Unmanned Little Bird helicopter. Boeing photo

Wherever there are computers, there is the potential for adversaries to attempt to subvert them for their own purposes.

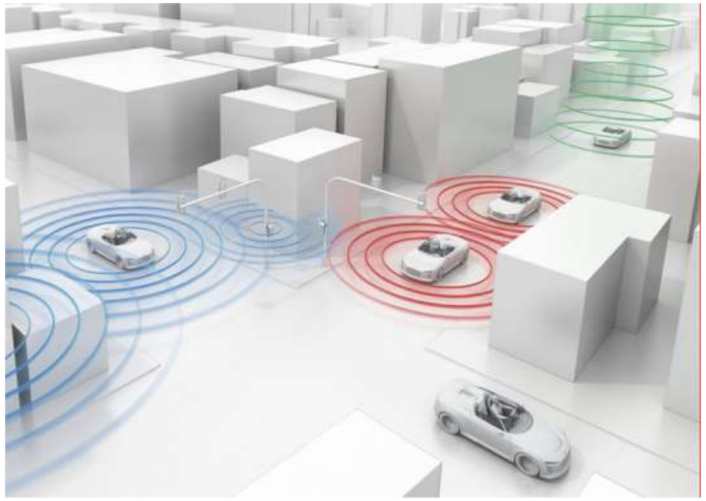
First the challenge: cyber-physical systems like aircraft are typically more resource constrained—including in connectivity—than desktop and enterprise systems (and even mobile systems). This means that desktop and enterprise security solutions relying on spare computing power, storage and always-on high-bandwidth networking, generally cannot be used on cyber-physical systems. This complicates the problem for cyber defense.

But here's the opportunity: cyber-physical systems are generally designed for a specific purpose and to interact with the physical world. In other words, their behaviors tend to be designed to achieve a physical result.

Application domains: Transportation



Safety, security, and control of autonomous cars



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


Courtesy of Florida Highway Patrol

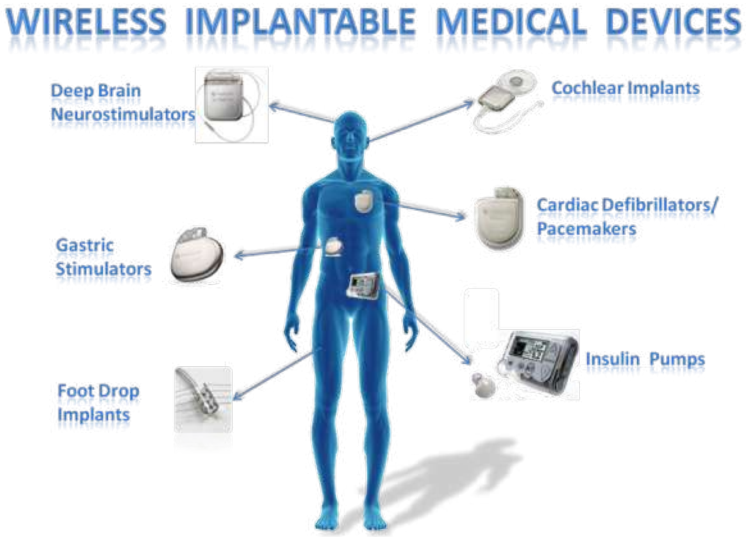
Application domains: Energy

- 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.

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

Application domains: Critical Infrastructure

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

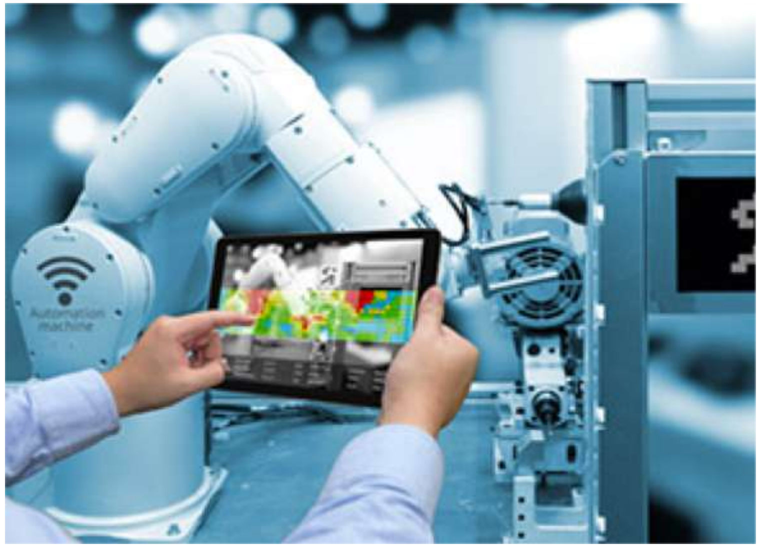
Structural health monitoring

Utility infrastructure- Gas, Electricity, Steam.

Application domains: … and many more

Agriculture

Manufacturing

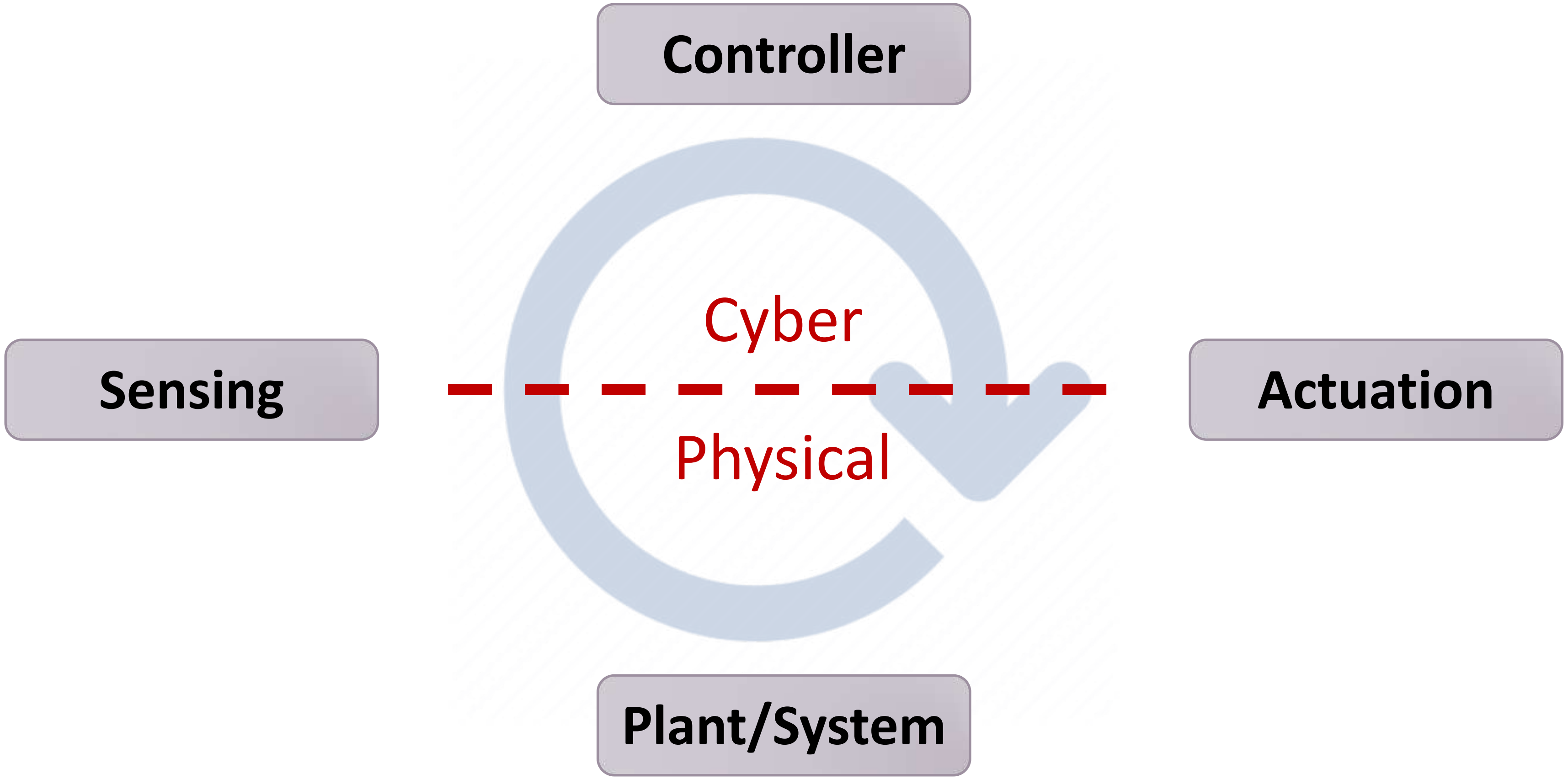


Industrial Control

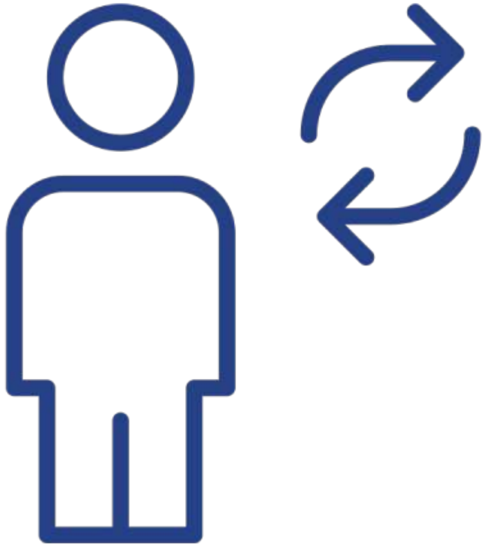
Characteristics of CPS

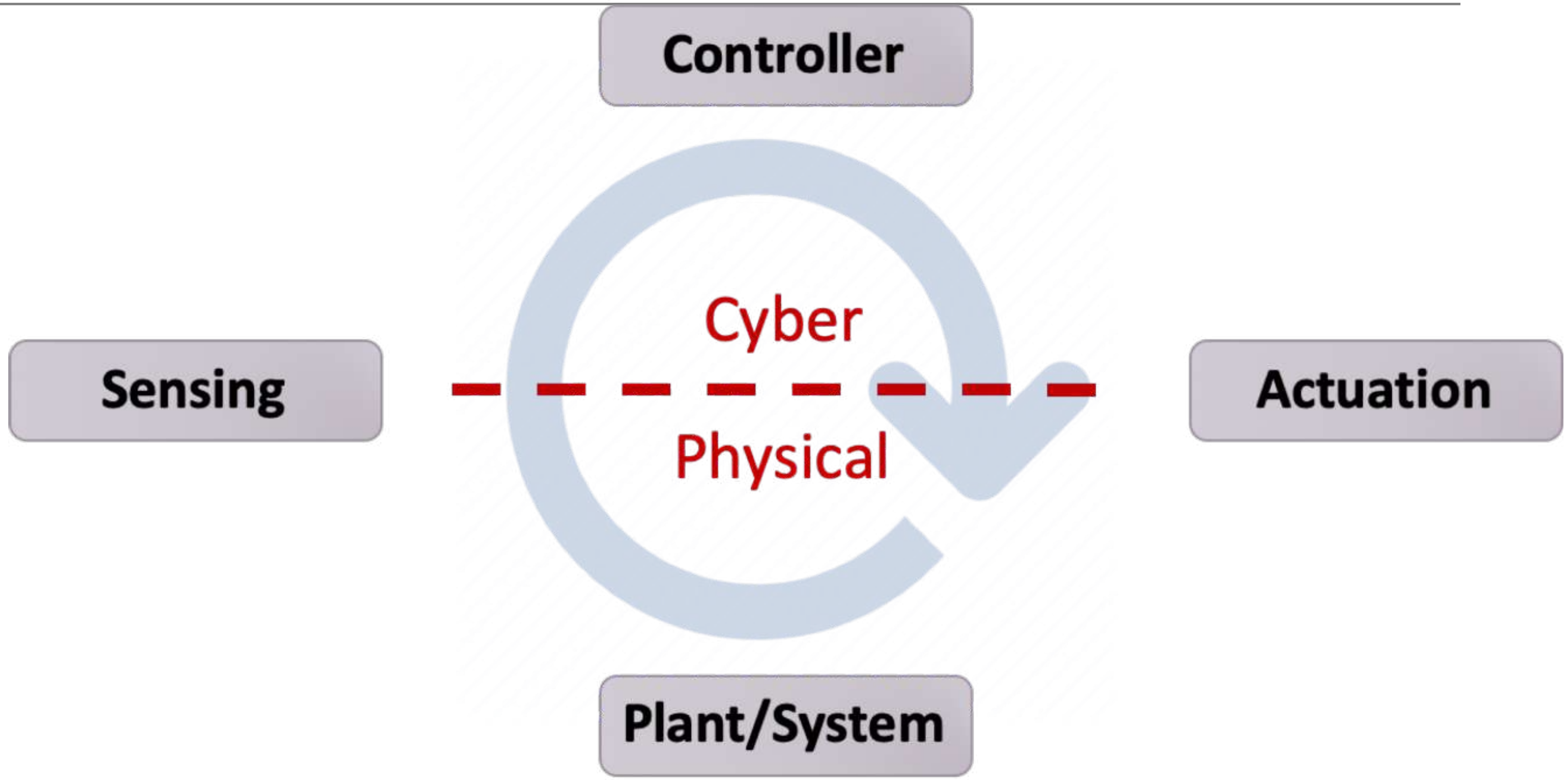
- Pervasive computation, sensing and control
- Networked at multi- and extreme scales
- Dynamically reorganizing/ reconfiguring
- High degrees of automation
- Dependable operation with *potential* requirements for high assurance of reliability, safety, security and usability
- With / without human in-the-loop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

Closing the loop



Human in the loop





Cyber-Physical Systems

Deeply integrating

computation, communication, control, **and humans**

into **physical systems**

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

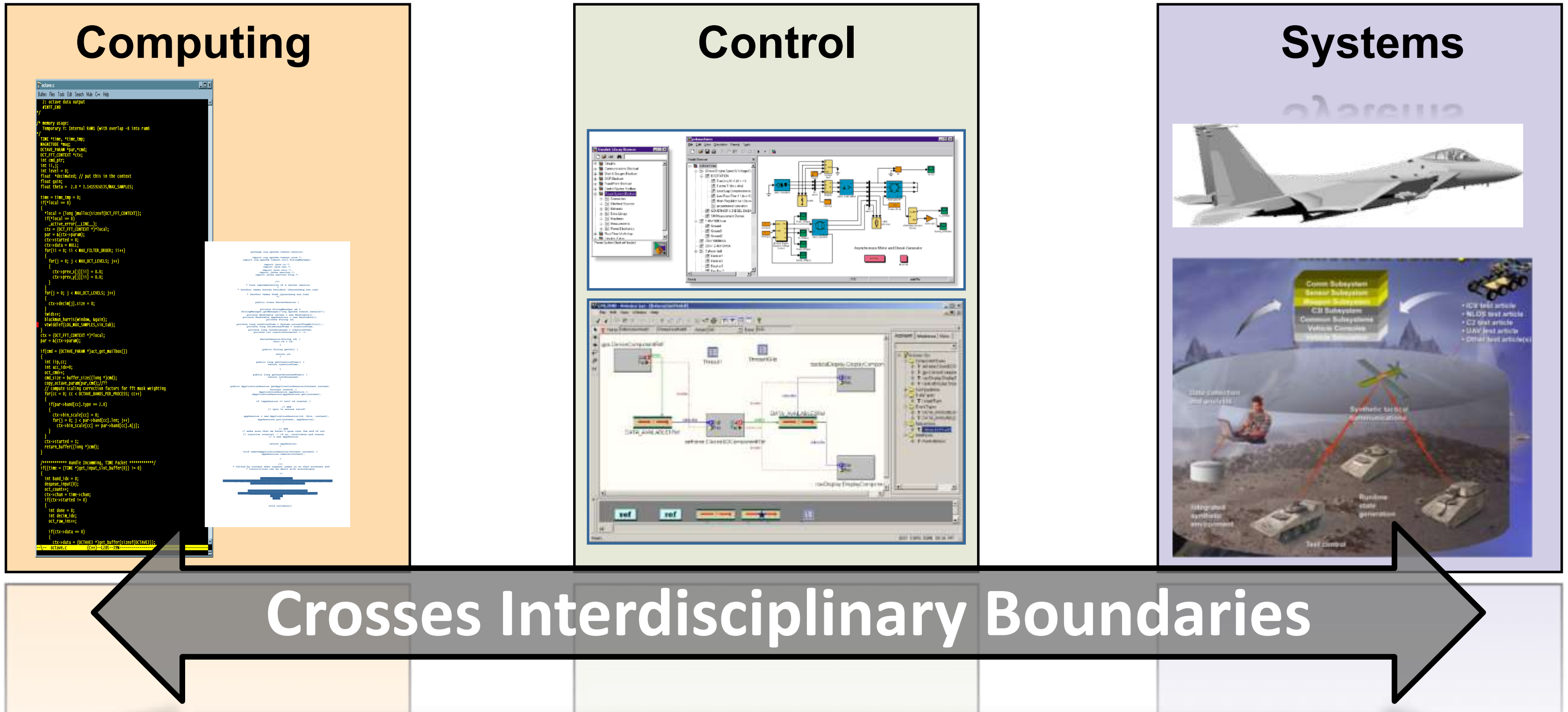
Cyber-Physical Systems - Goals

Transform how we interact with the physical world

Fusion of physical and computational sciences

Produce significant impact on society

Why is CPS hard ?



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 ?

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

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

what is this course about ?

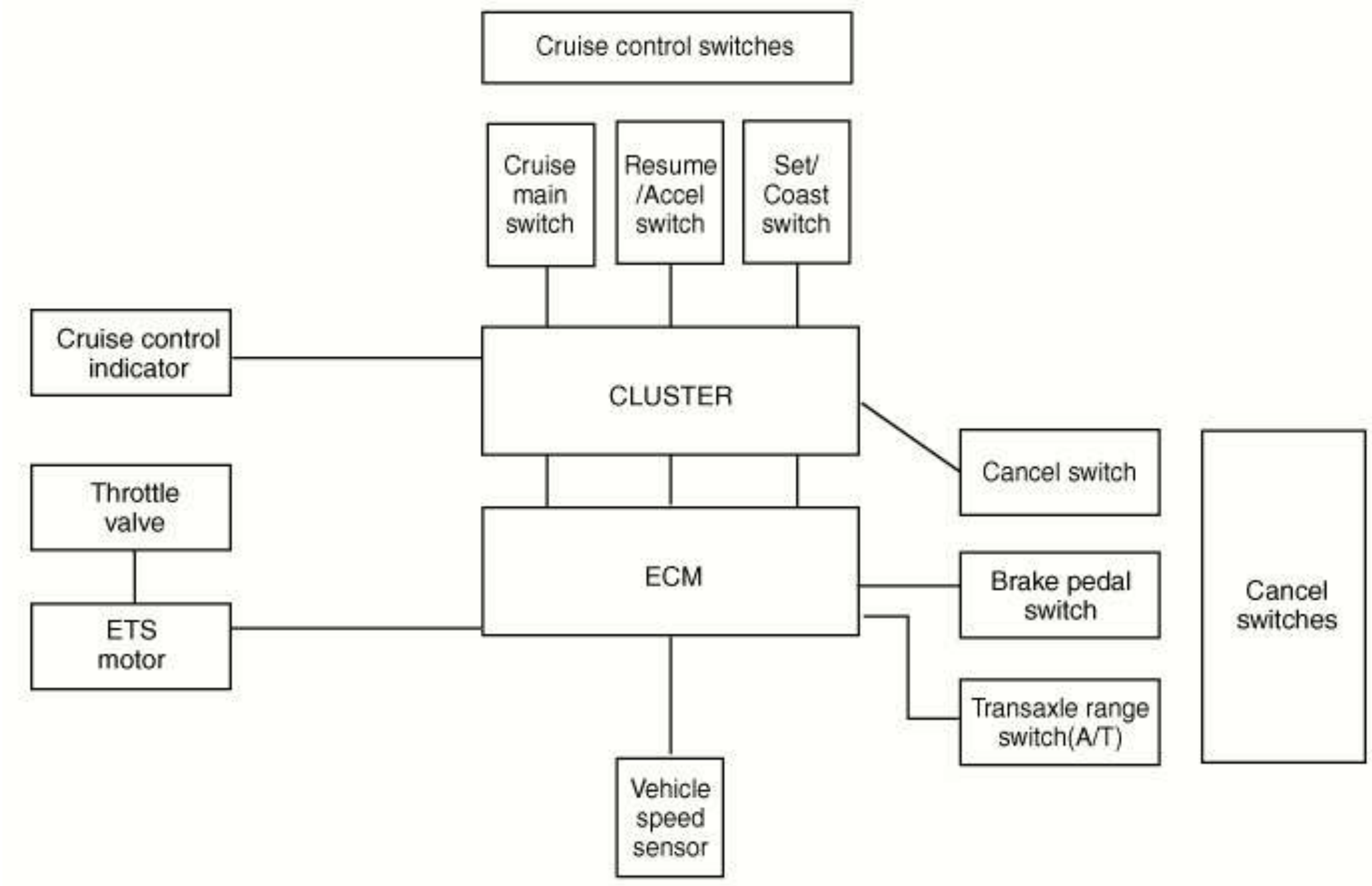
Principles of **Modeling** for Cyber-Physical Systems

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 ?

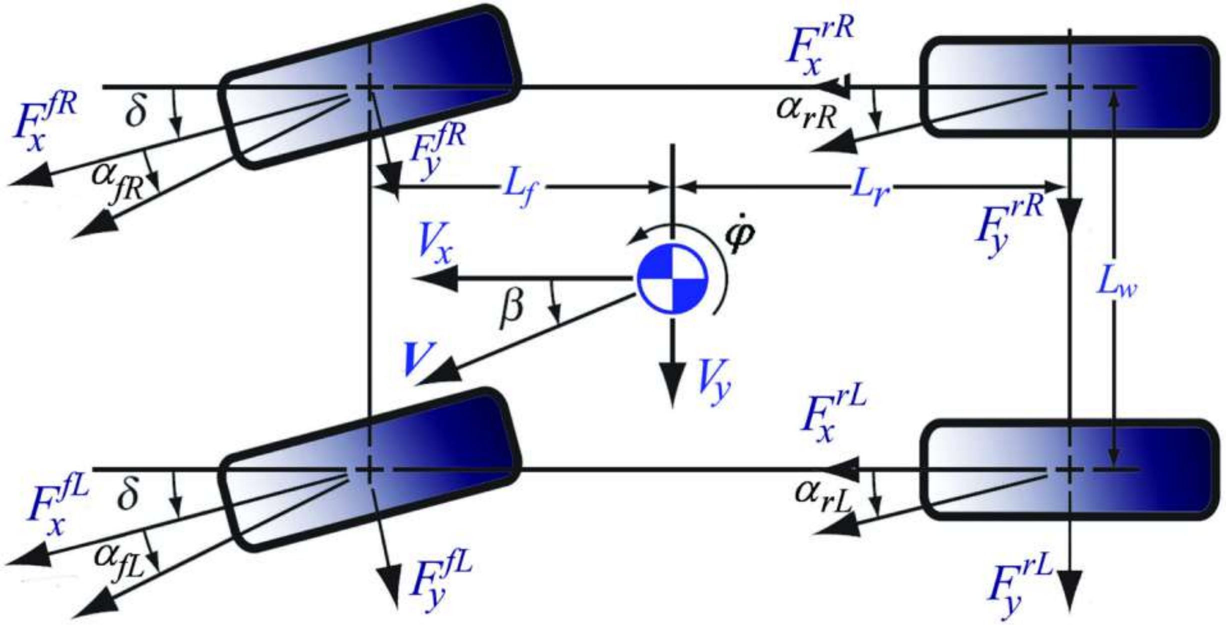
Modeling types: Physical modeling

Modeling types: Functional/compositional modeling



Do you know of any tools for functional modeling ?

Modeling types: Mathematical modeling

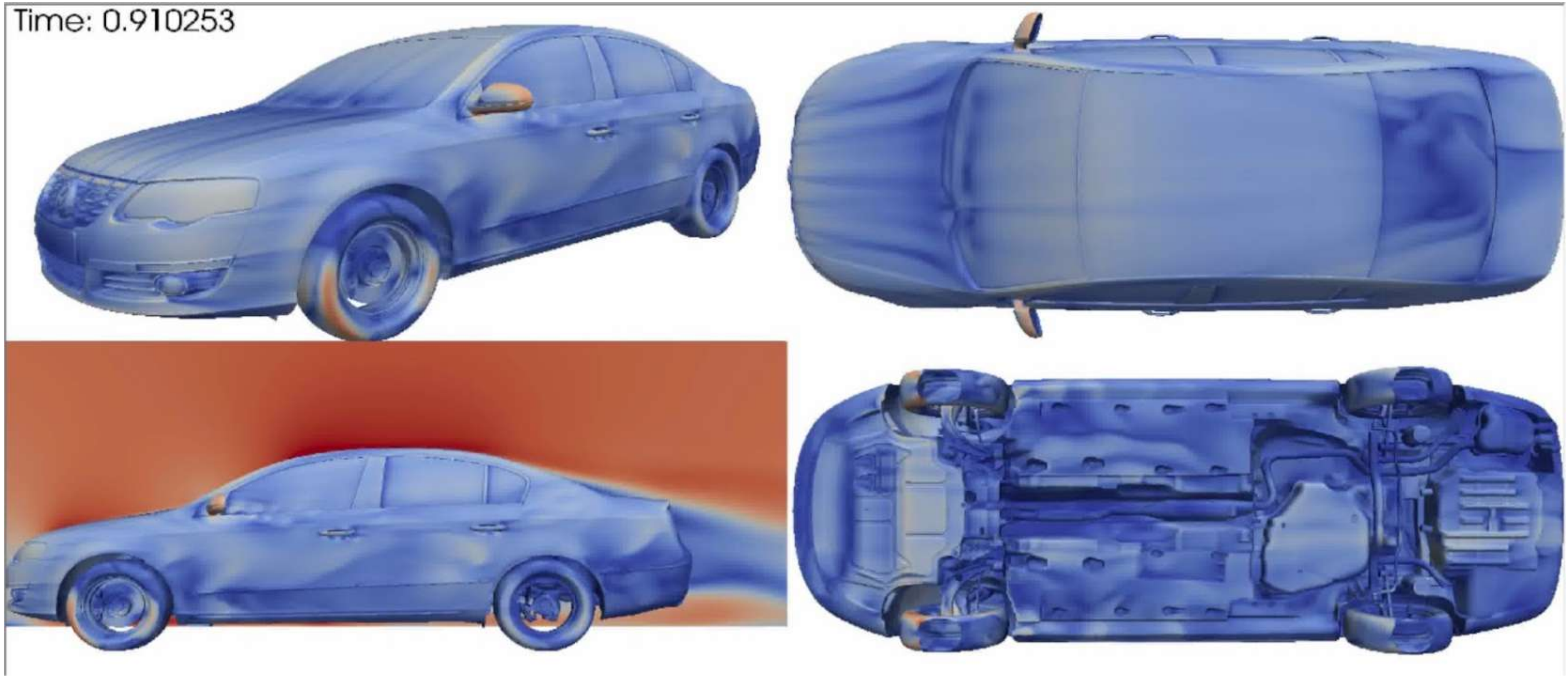


$$\dot{v}_x = \frac{1}{m}\left[\left(F_x^{fL} + F_x^{fR}\right)\cos\delta - \left(F_y^{fL} + F_y^{fR}\right)\sin\delta + \left(F_x^{rL} + F_x^{rR}\right) + \dot{\varphi} v_y\right],$$

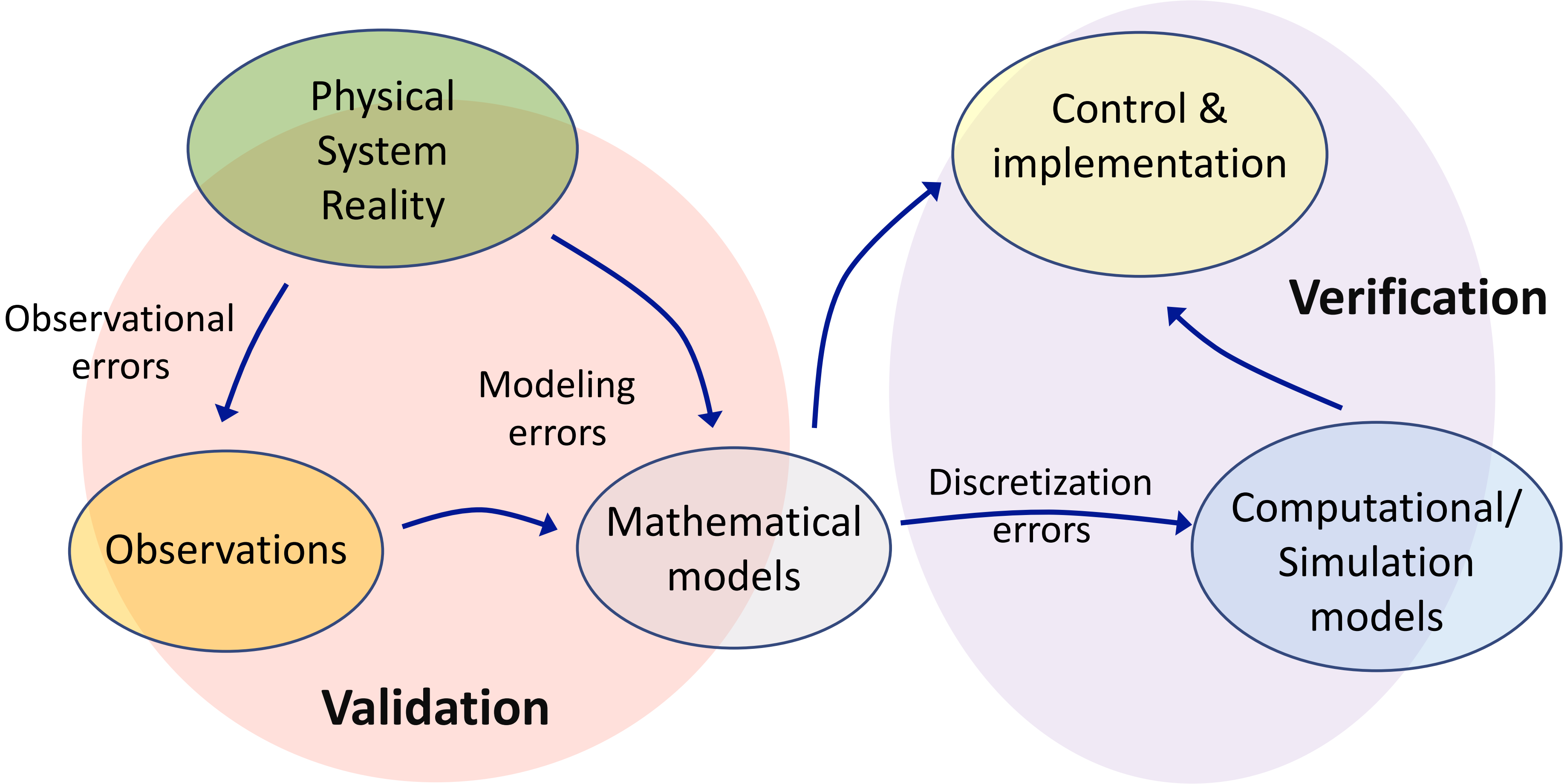
$$\dot{v}_y = \frac{1}{m}\left[\left(F_y^{fL} + F_y^{fR}\right)\cos\delta + \left(F_x^{fL} + F_x^{fR}\right)\sin\delta + \left(F_y^{rL} + F_y^{rR}\right) - \dot{\varphi} v_x\right],$$

$$\ddot{\varphi} = \frac{1}{I_\varphi}\left\{L_f\left(F_x^{fL} + F_x^{fR}\right)\sin\delta + L_f\left(F_y^{fL} + F_y^{fR}\right)\cos\delta - L_r\left(F_y^{rL} + F_y^{rR}\right)\right.$$
$$\left. + \frac{L_w}{2}\left(F_x^{fR} - F_x^{fL}\right)\cos\delta + \frac{L_w}{2}\left(F_x^{rR} - F_x^{rL}\right) + \frac{L_w}{2}\left(F_y^{fL} - F_y^{fR}\right)\sin\delta\right\},$$

Modeling types: Computational modeling



A word about mathematical models

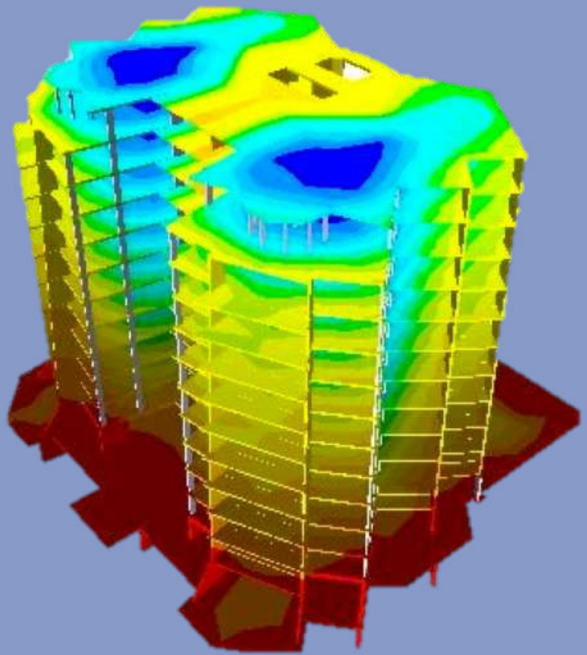


"Essentially all models are wrong, but some are useful"

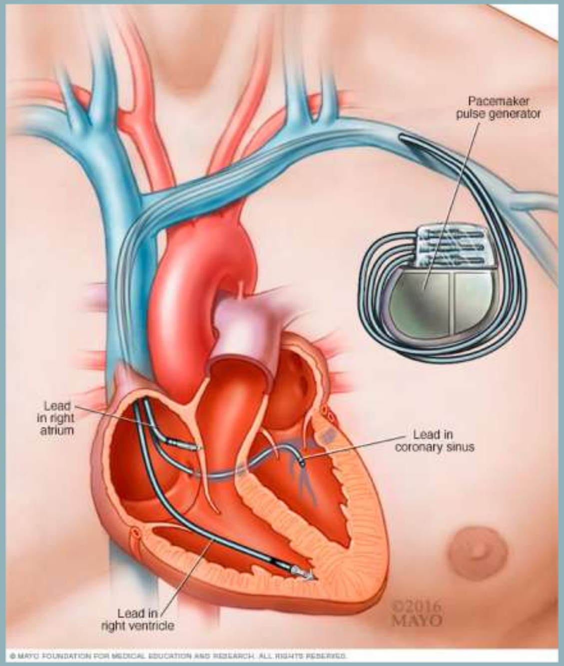
- George E.P. Box (statistician)

….this course is about building useful models.

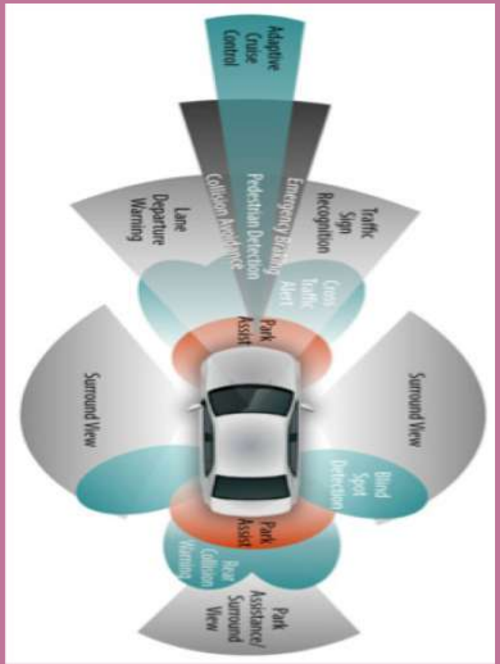
This course: Three CPS domains



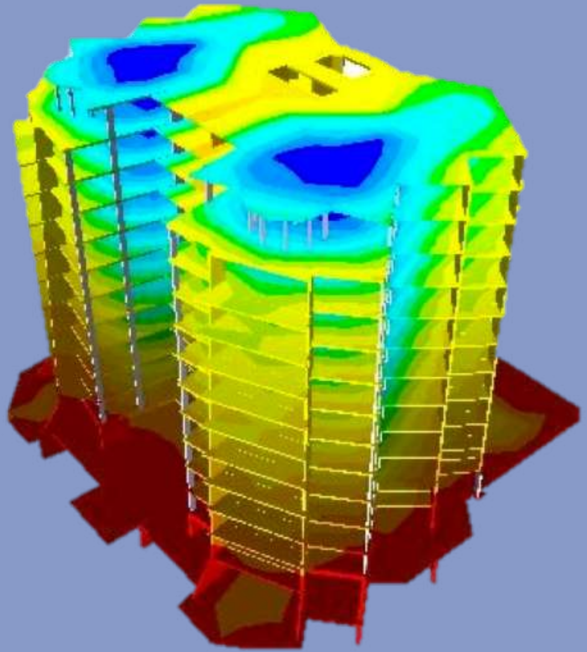
Energy CPS



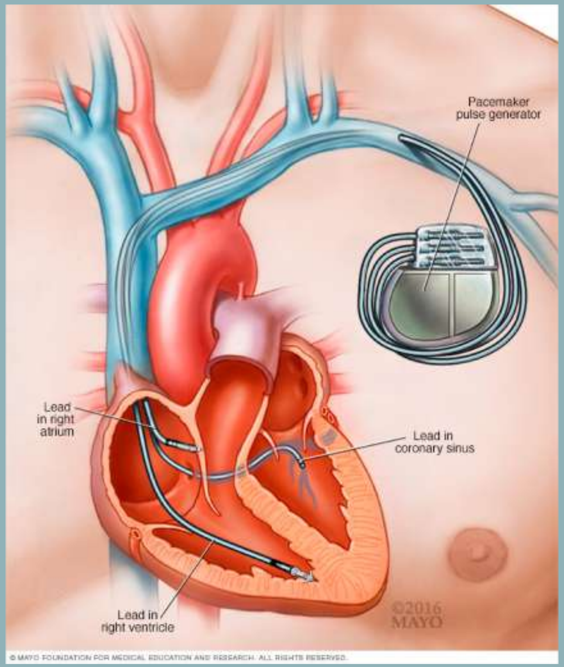
Medical CPS



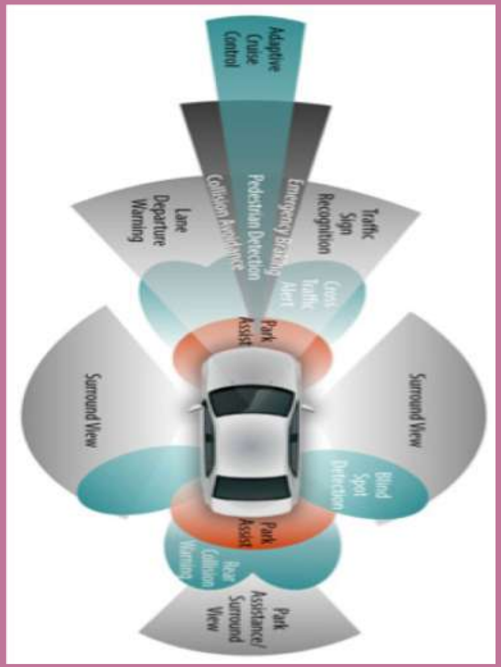
Automotive CPS



Energy CPS

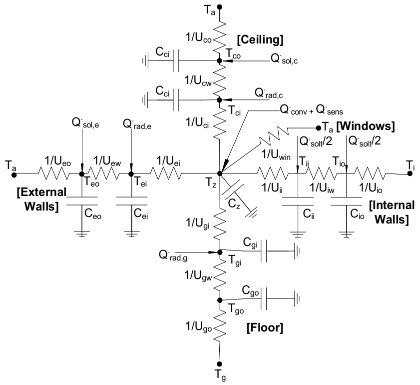


Medical CPS

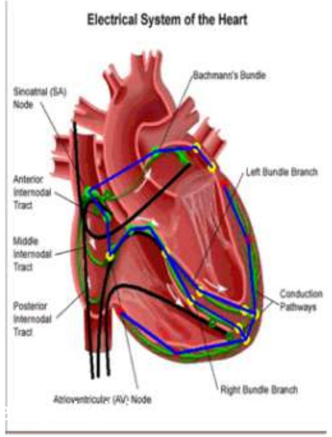


Automotive CPS

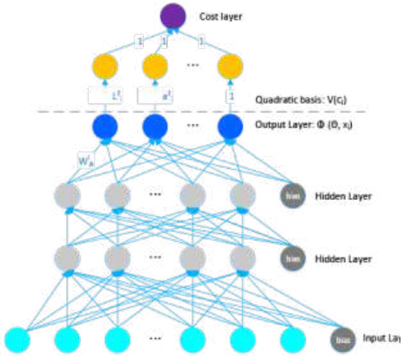
White-box State-space

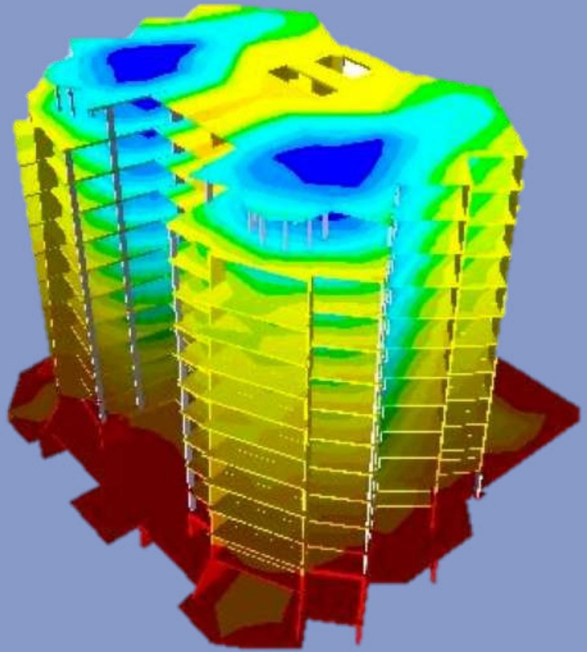


Timed Automata

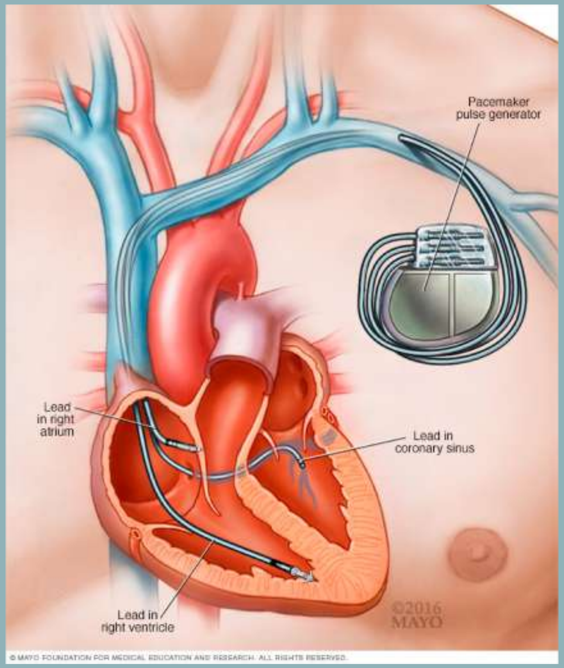


Data-driven

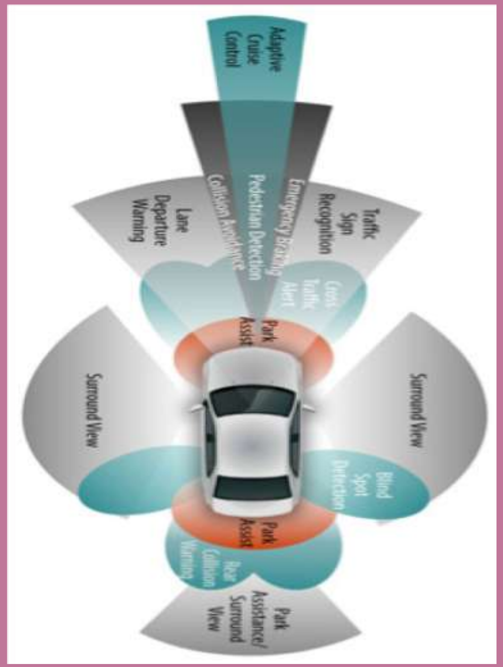




Energy CPS



Medical CPS



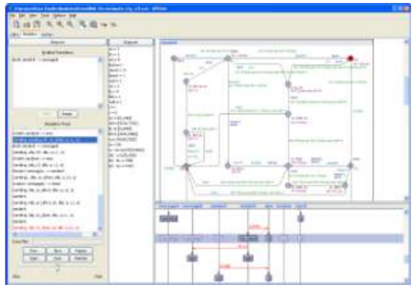
Automotive CPS

EnergyPlus

Matlab

UPPAAL

Simulink



TensorFlow

Python

Energy CPS Module

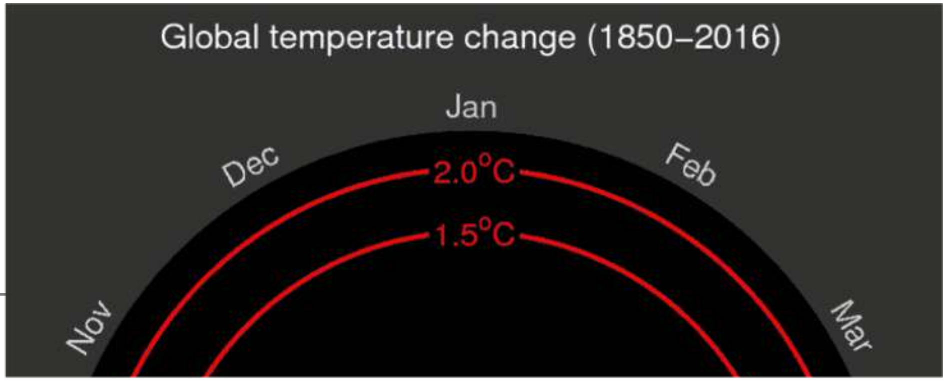
RIBE SCIENTIFIC AMERICAN. English Cart 0 Sign In |

THE SCIENCES MIND HEALTH TECH SUSTAINABILITY EDUCATION VIDEO PODCASTS BLOGS STORE

2014 Officially Hottest Year on Record

THE SCIENCES MIND HEALTH TECH SUSTAINABILITY EDUCATION VIDEO PODCASTS BLOGS ST

2015 Is Officially the Hottest Year

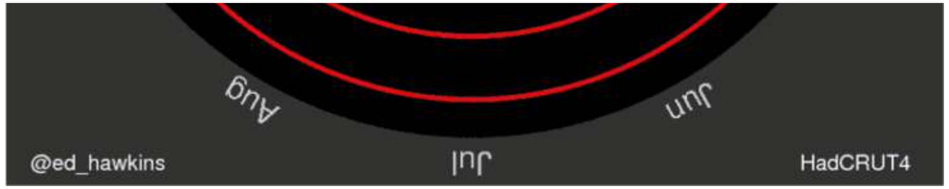


EARTH

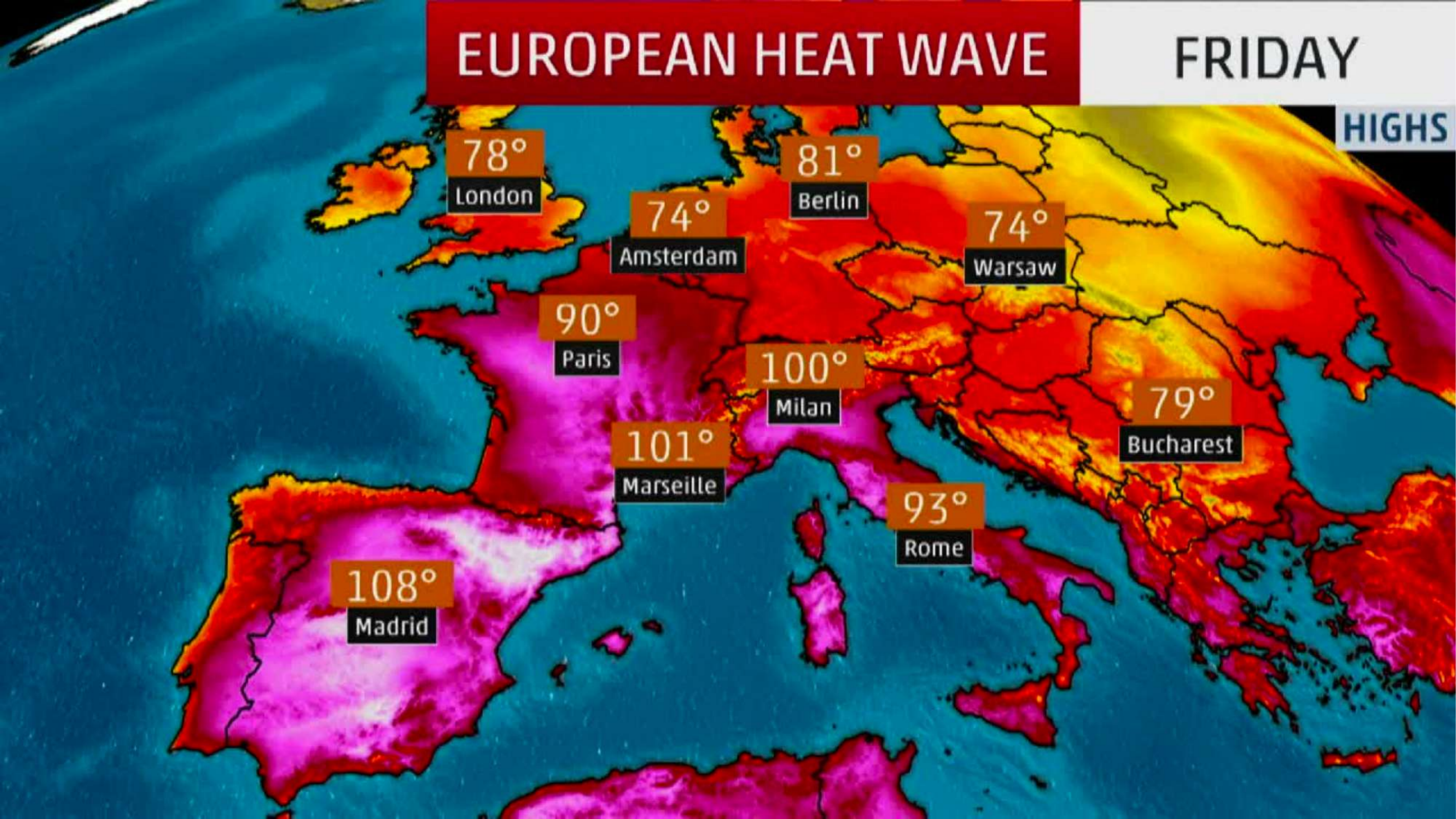
July Was the Hottest Month in Recorded History

After a record-breaking heat wave in Europe and the Arctic, last month edged out July 2016

on Record for the U.S.



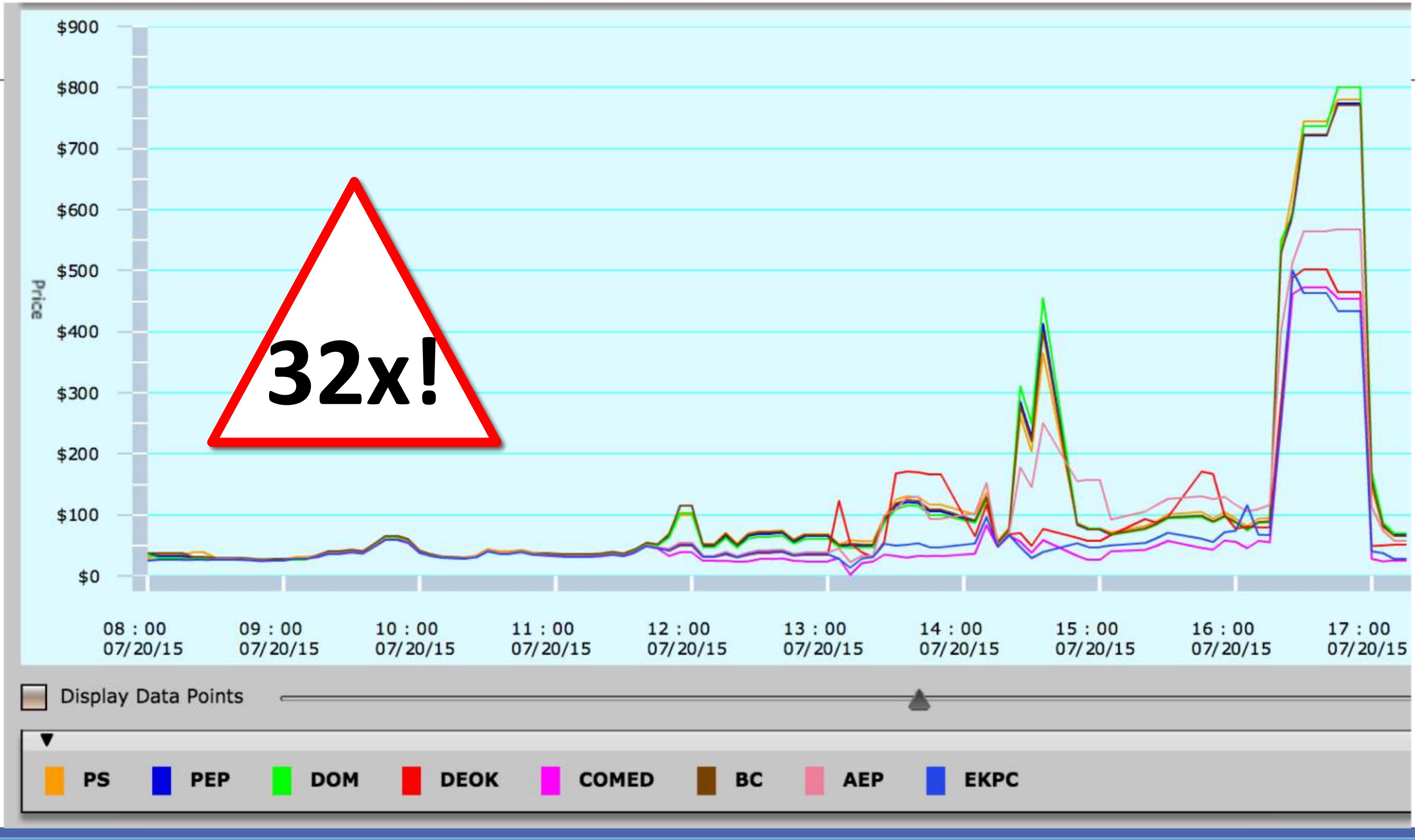
2018 Was the 4th Warmest Year on Record, Berkeley Group Announces


EUROPEAN HEAT WAVE
FRIDAY
HIGHS
78°
London
81°
Berlin
74°
Amsterdam
74°
Warsaw
90°
Paris
100°
Milan
79°
Bucharest
101°
Marseille
93°
Rome
108°
Madrid

Price Volatility: Summer peak

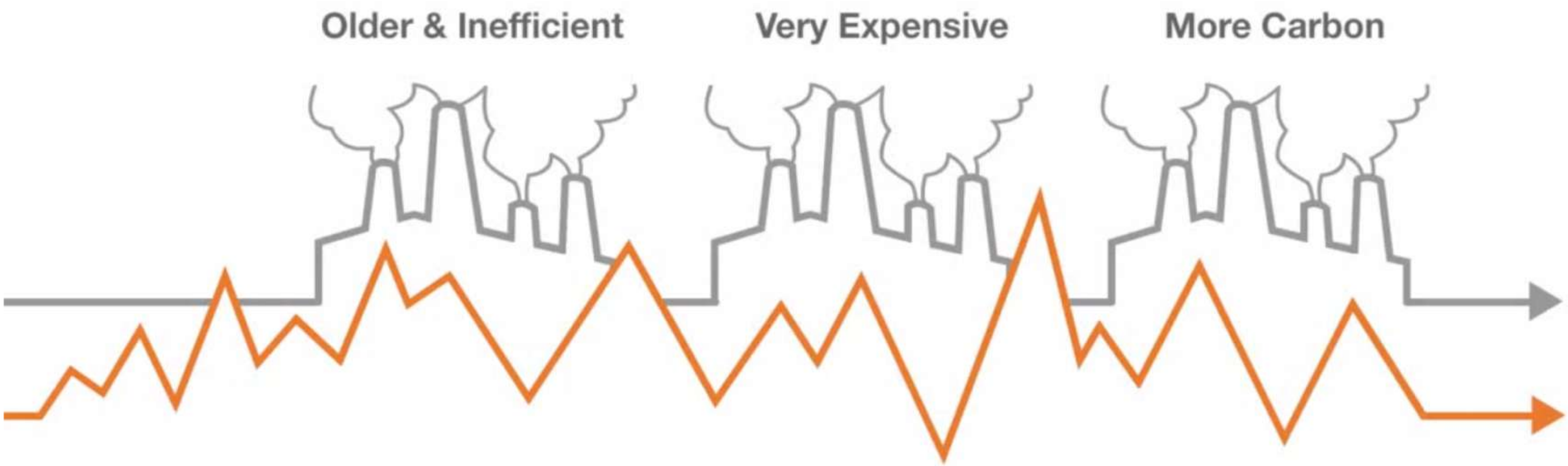
Nominal price: $25/MWh

Peak Price: $800/MWh



20th, July 2015

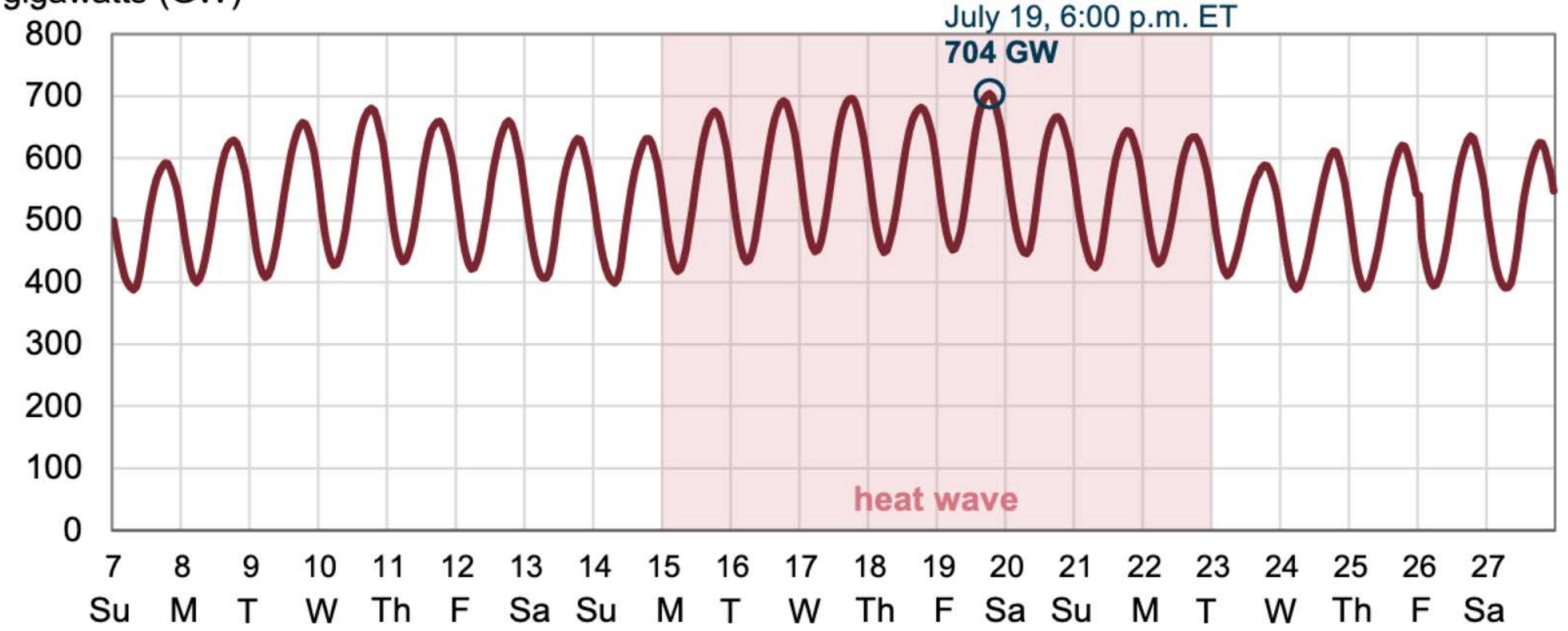
“All kilowatts are not created equally”



AUGUST 1, 2019

Heat wave results in highest U.S. electricity demand since 2017

Hourly electricity demand in the Lower 48 states (Jul 7-Jul 27, 2019)
gigawatts (GW)

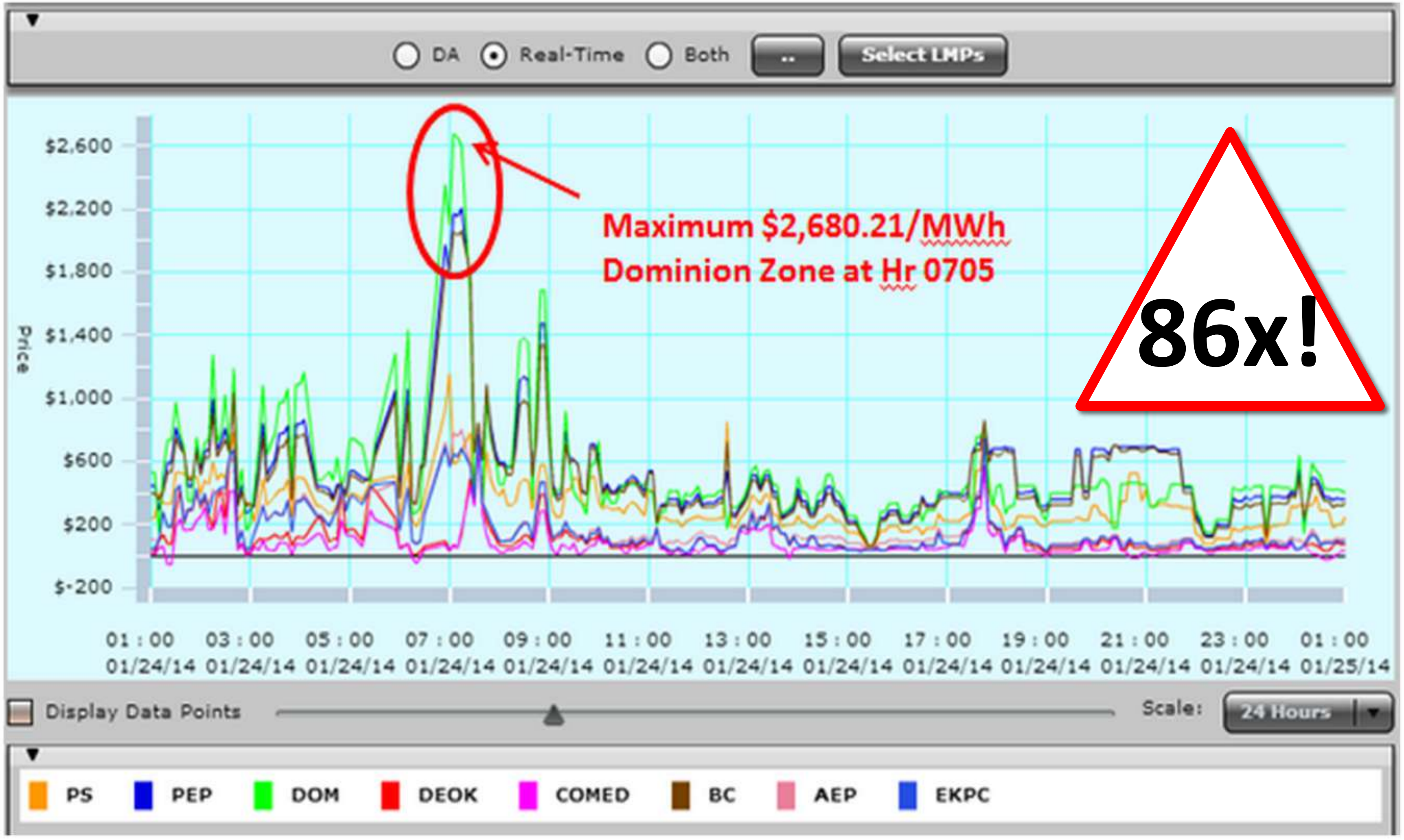


Source: U.S. Energy Information Administration, *U.S. Electric System Operating Data*

Price Volatility: Winter peak

Nominal price: $31.21/MWh

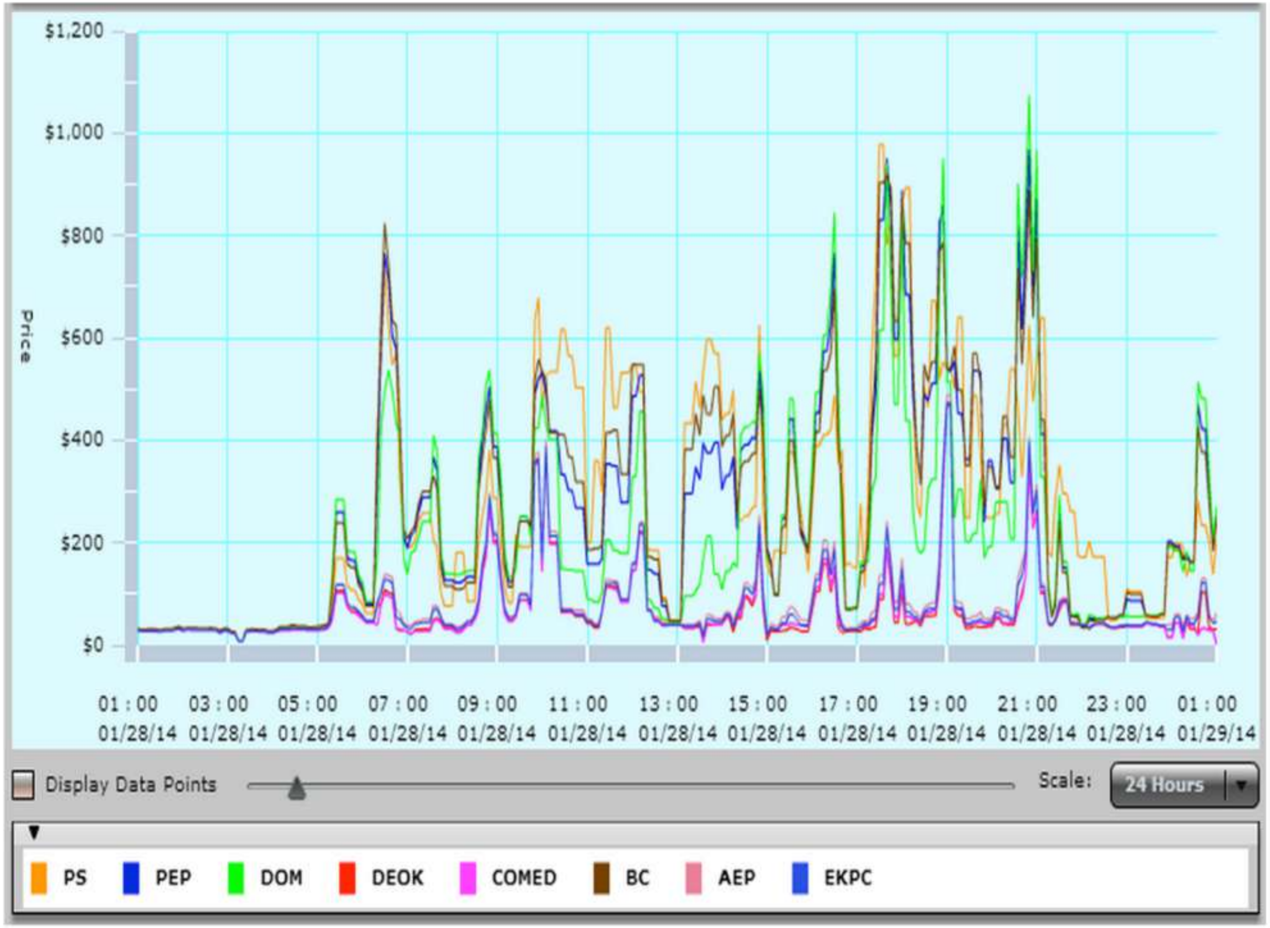
Peak Price: $2,680.21/MWh



24th, January 2014

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

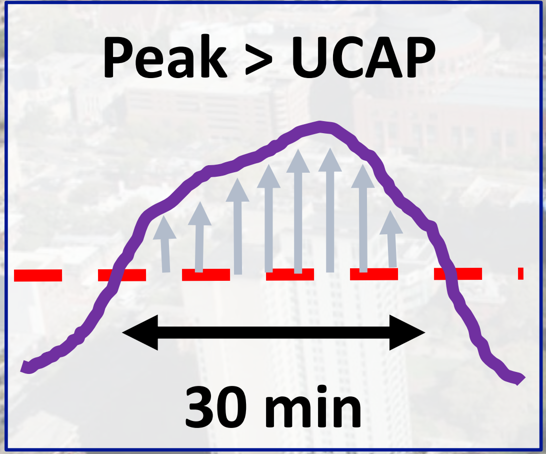
4 Million
Gallons of chilled water (@42F)

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

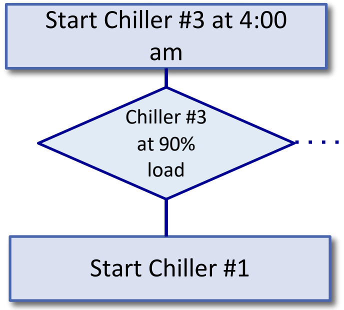
70% Portion of electricity consumption in the United States

1/3 Portion of global total CO_2 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.

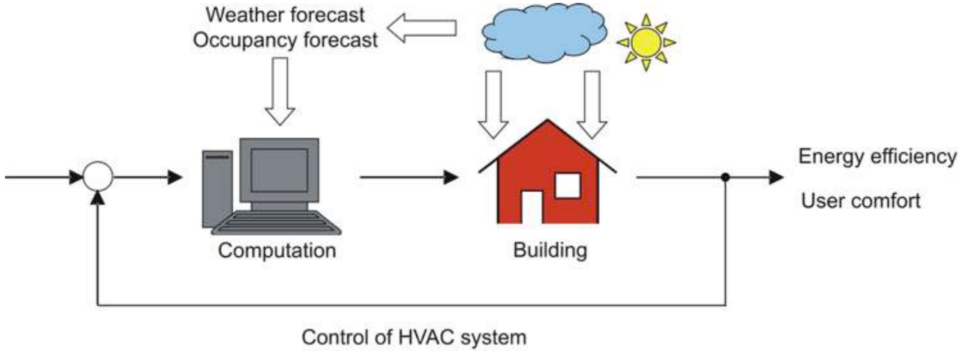


Took 23 min yesterday

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)

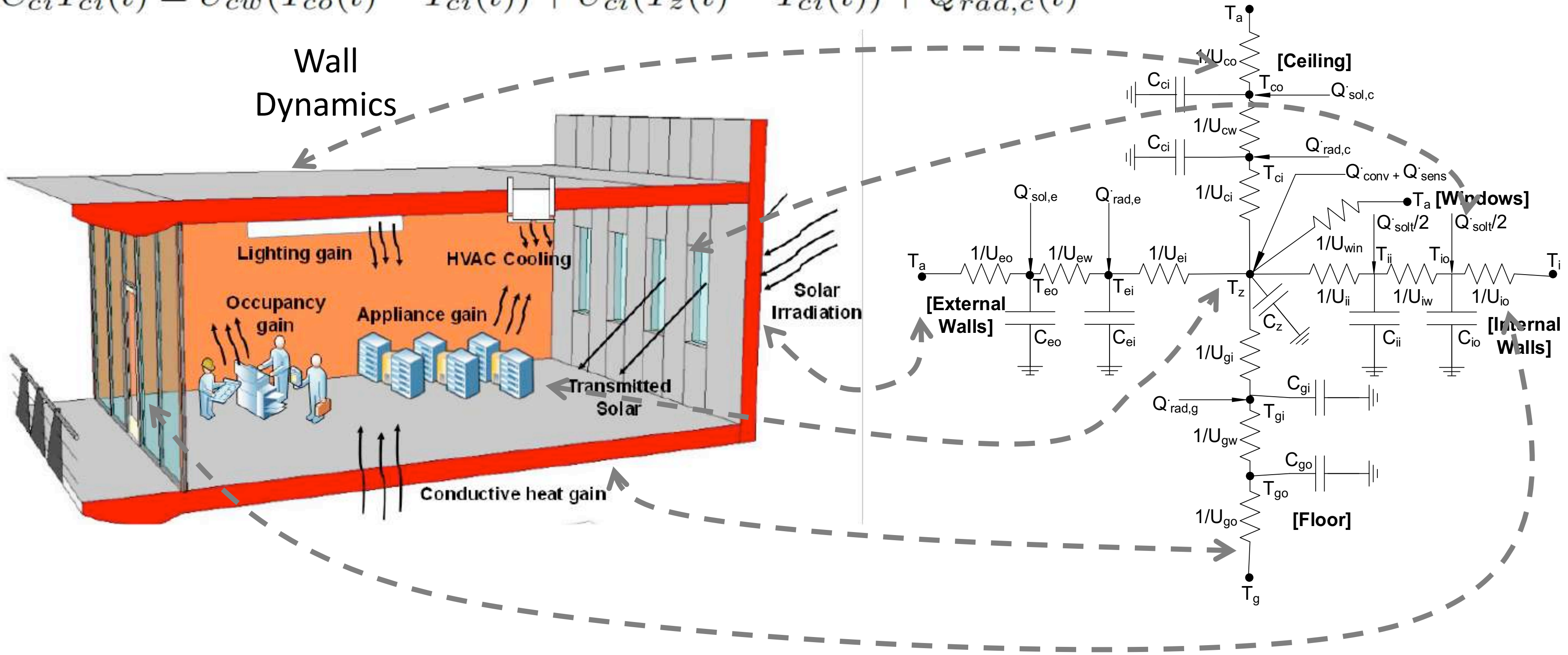
The control problem in buildings

Integrated control of:

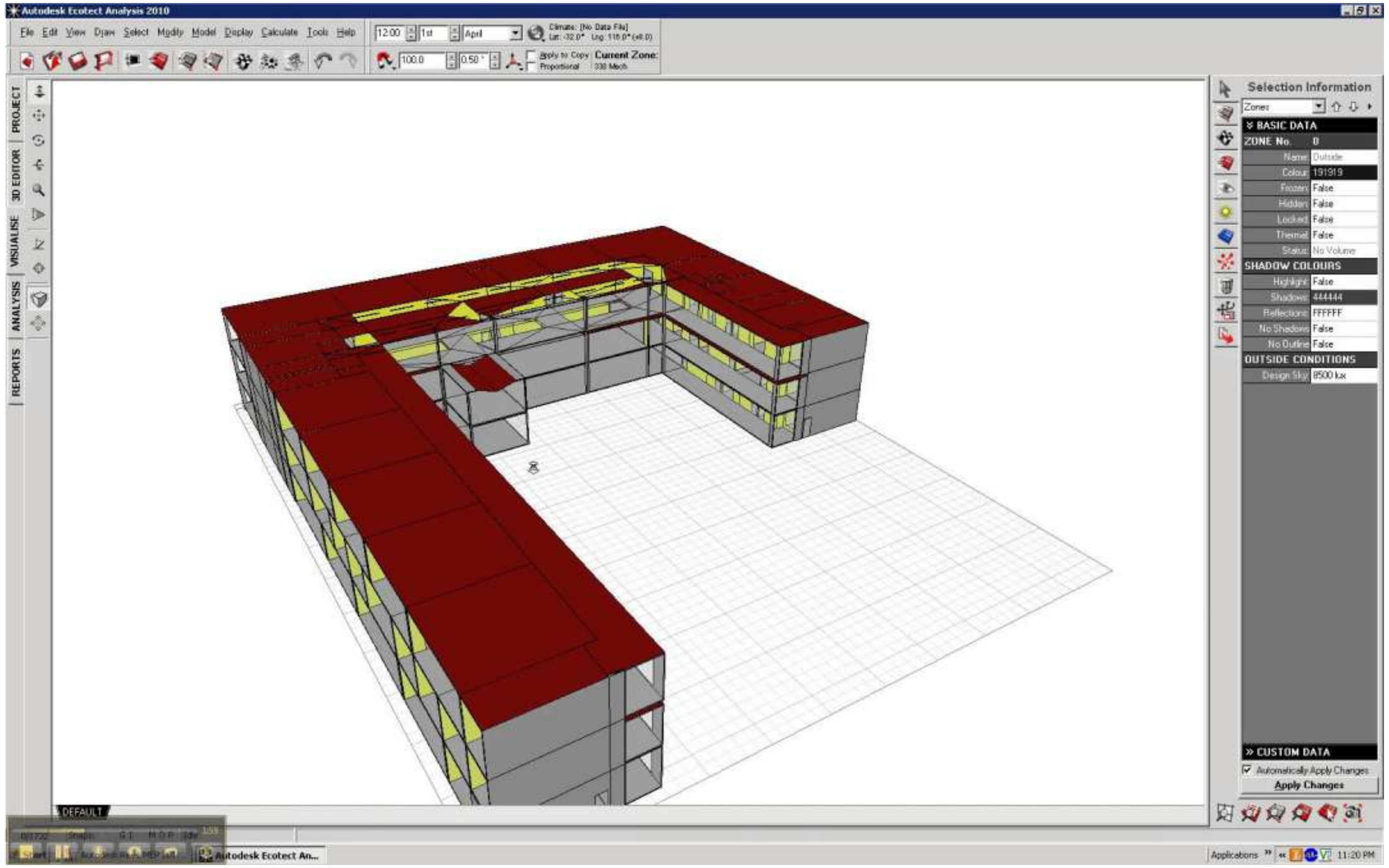
- Heating
- Cooling
- Ventilation
- Lighting
- Blinds

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

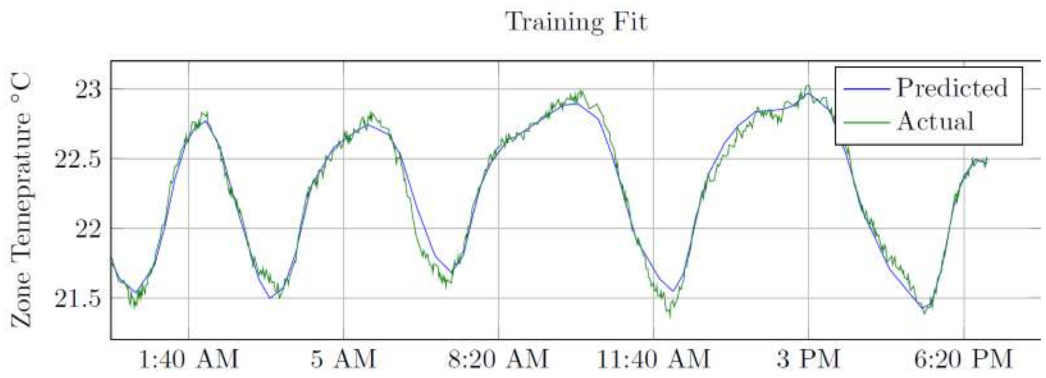


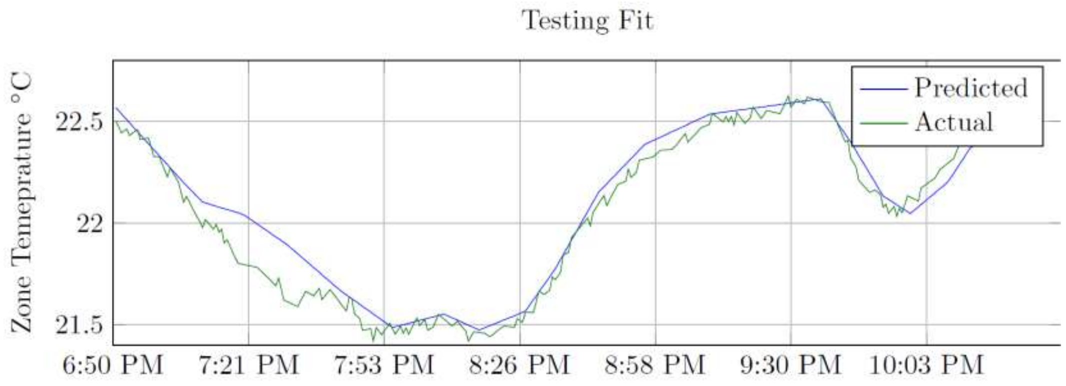
Using EnergyPlus.

Generating input-output data

Modeling a building in MATLAB

Non-linear parameter estimation and model validation





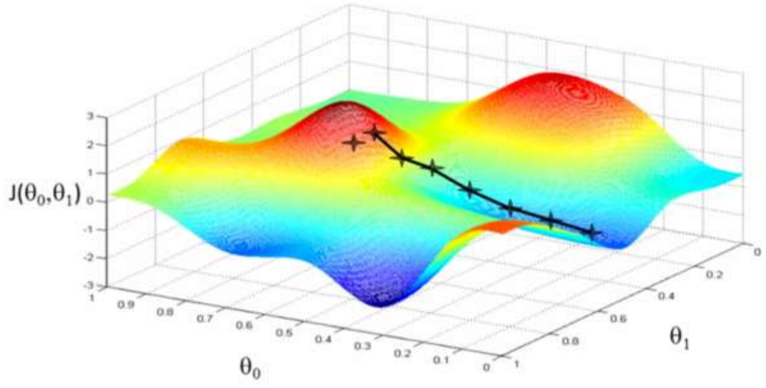
Model Accuracy for Training data

RMSE: 0.062 °C
$R2$: 0.983

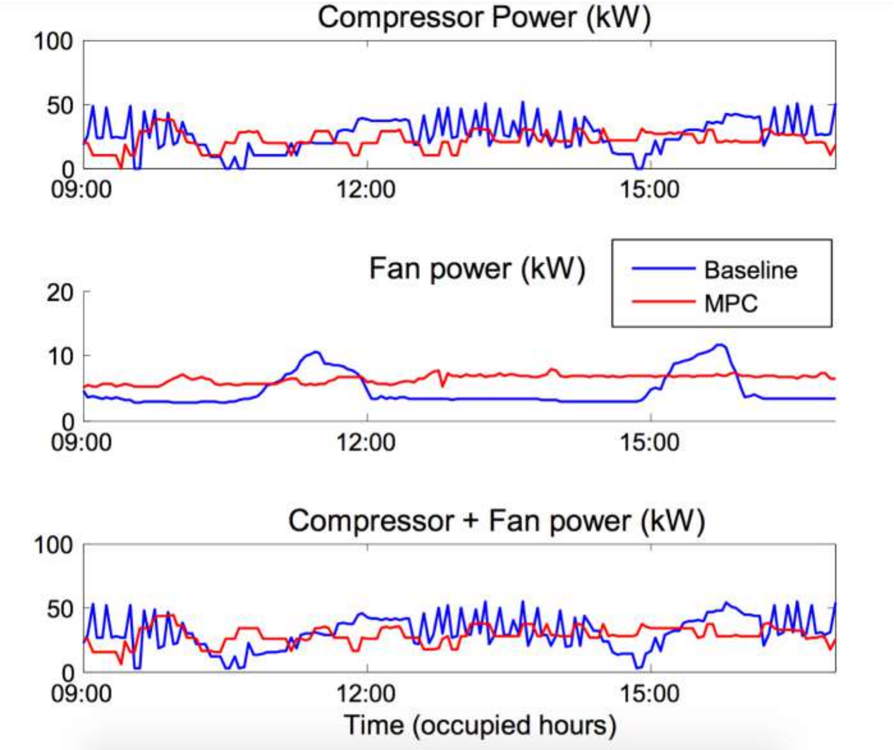
Baseline

Model Accuracy for Test Data

RMSE: 0.091 °C
$R2$: 0.948



Predictive control



Medical CPS Module

Software related vehicle recalls

Implantable devices recall

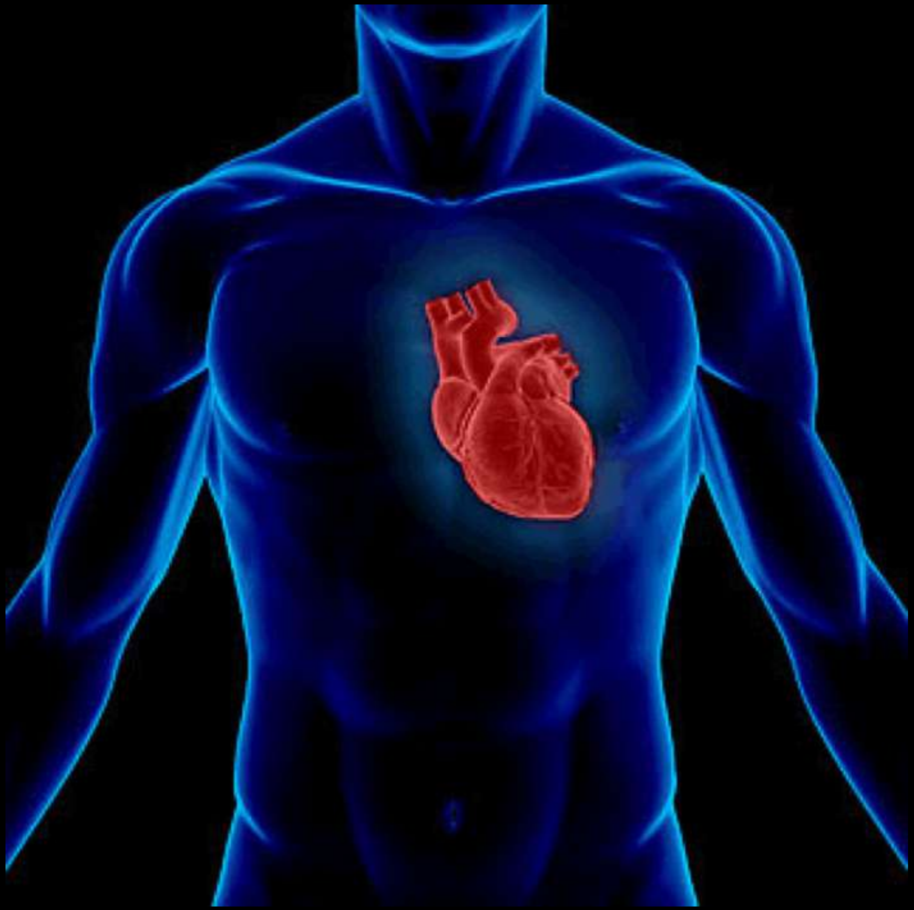
- Over 600,000 cardiac medical devices recalled from 1990-2000
  - 40% of which were due to software issues

- 2008-12: **15% of *all*** the medical device recalls due to software

Implantable Pacemaker

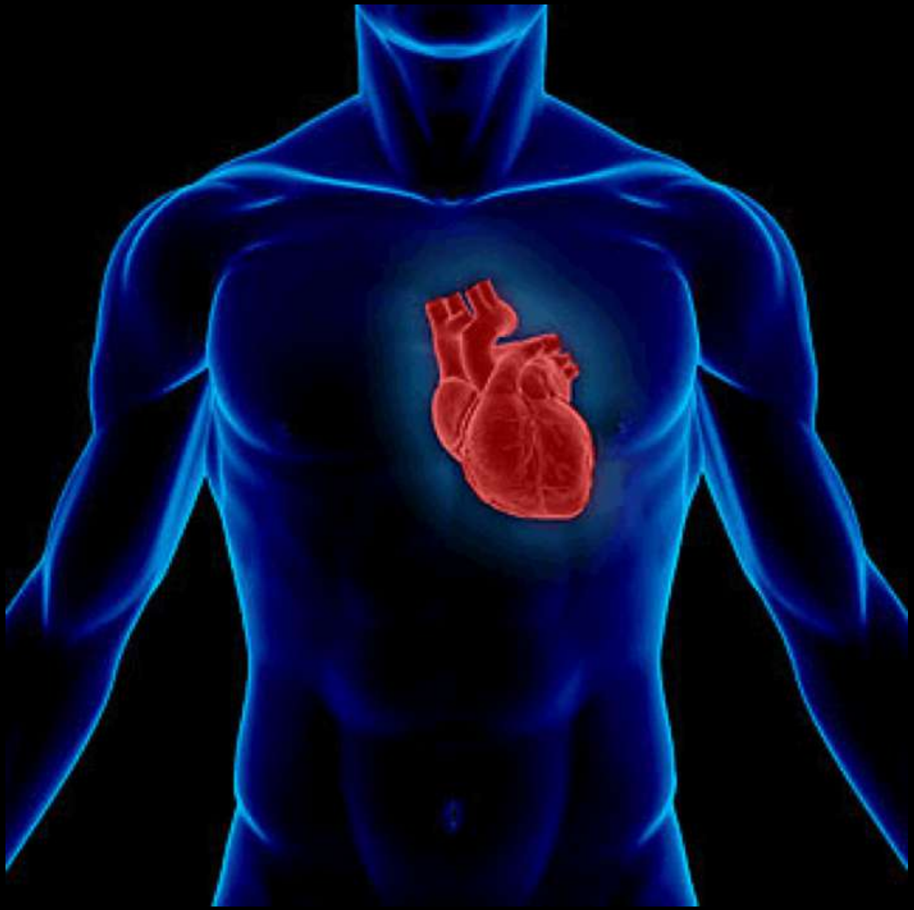
Implantable Cardioverter-Defibrillator (ICD)

The Heart



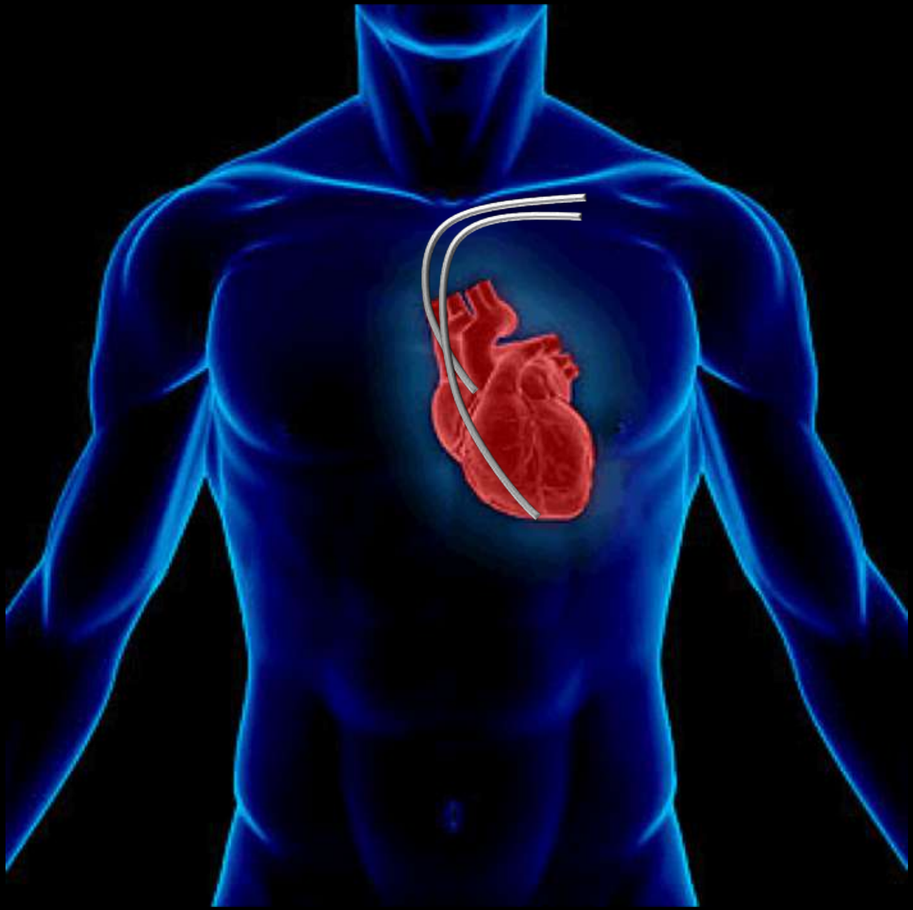
- Muscle contraction triggered by electrical signals

BRADYCARDIA



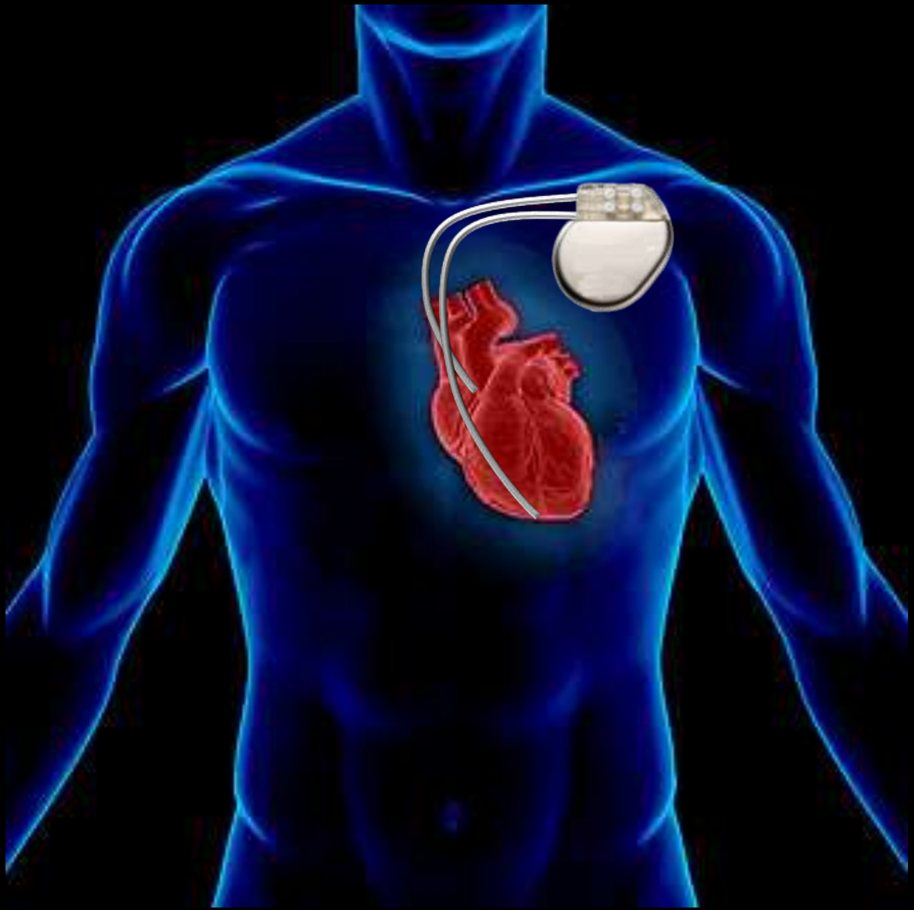
- Slow generation and conduction of electrical signals
- Slow heart rate
- Symptom: fainting, dizziness
- Could lead to heart attack

Implantable Pacemaker



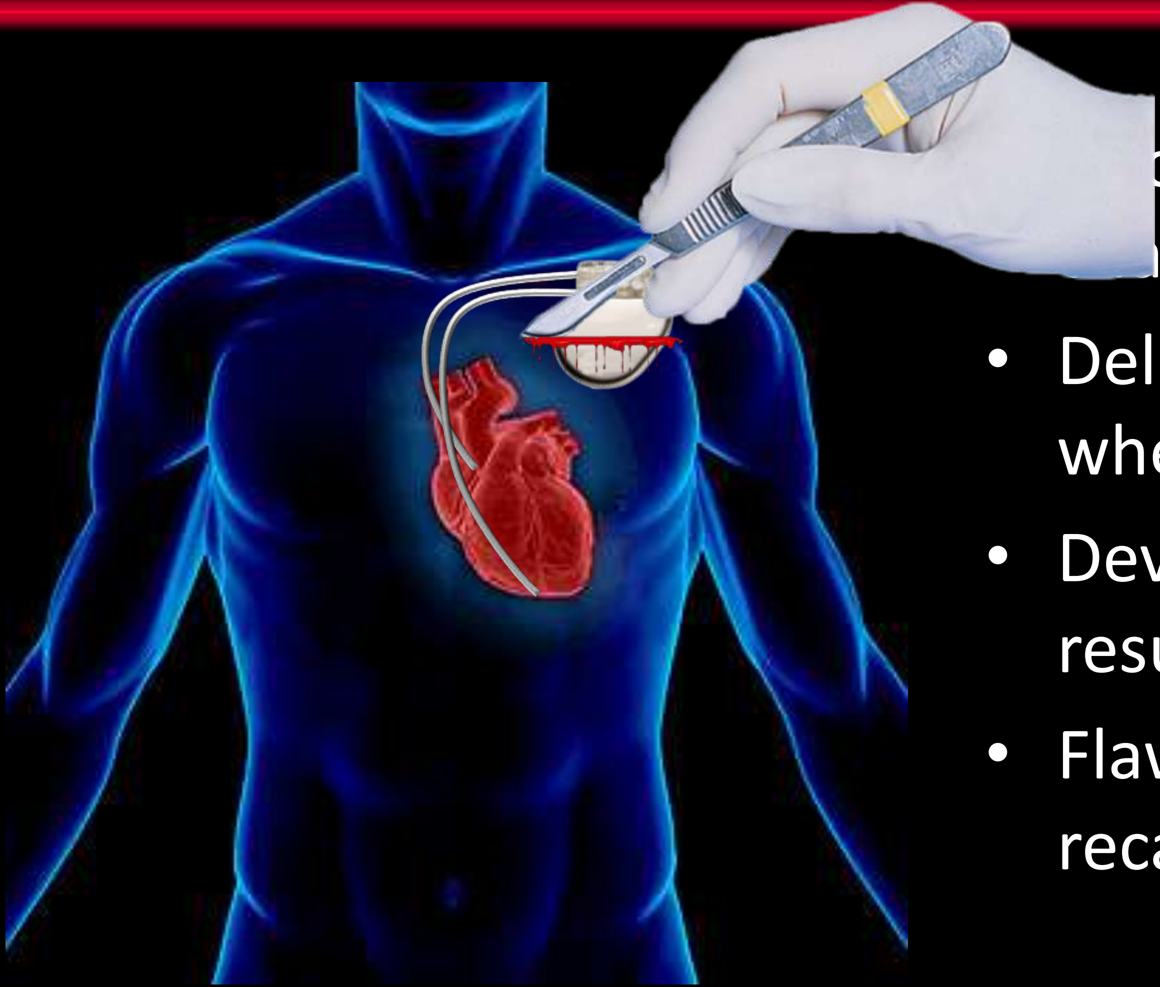
- o leads in heart chambers

Implantable Pacemaker



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

Implantable Pacemaker



- o leads in heart mbers
- 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

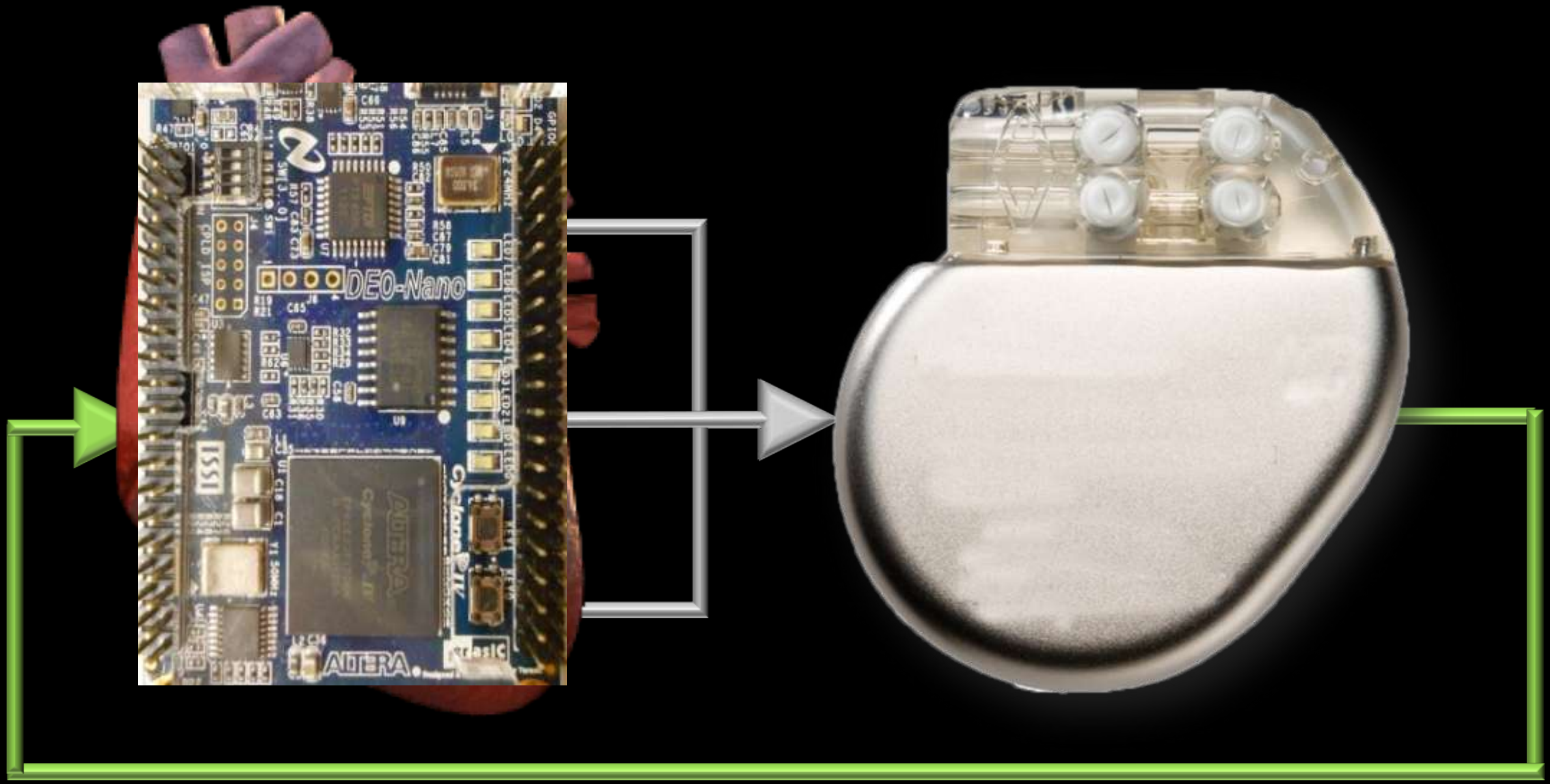
The physical plant:

Complex dynamics of the heart

Interaction between the heart and the body

Domain knowledge

Closed-Loop Evaluation

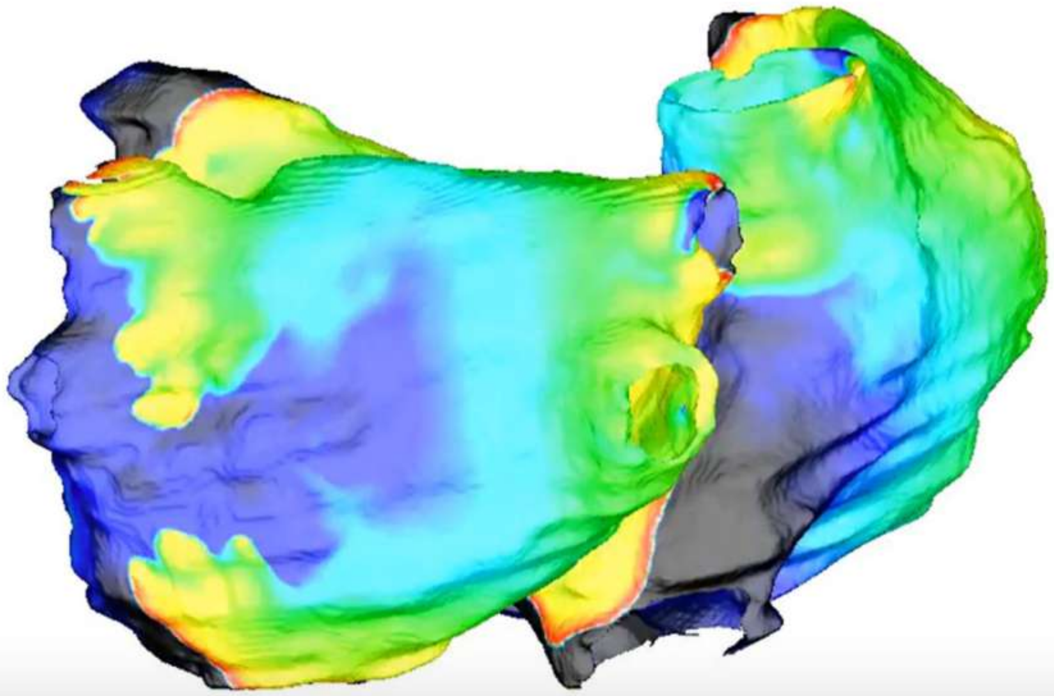


22 Aug 2019 | 12:00 GMT

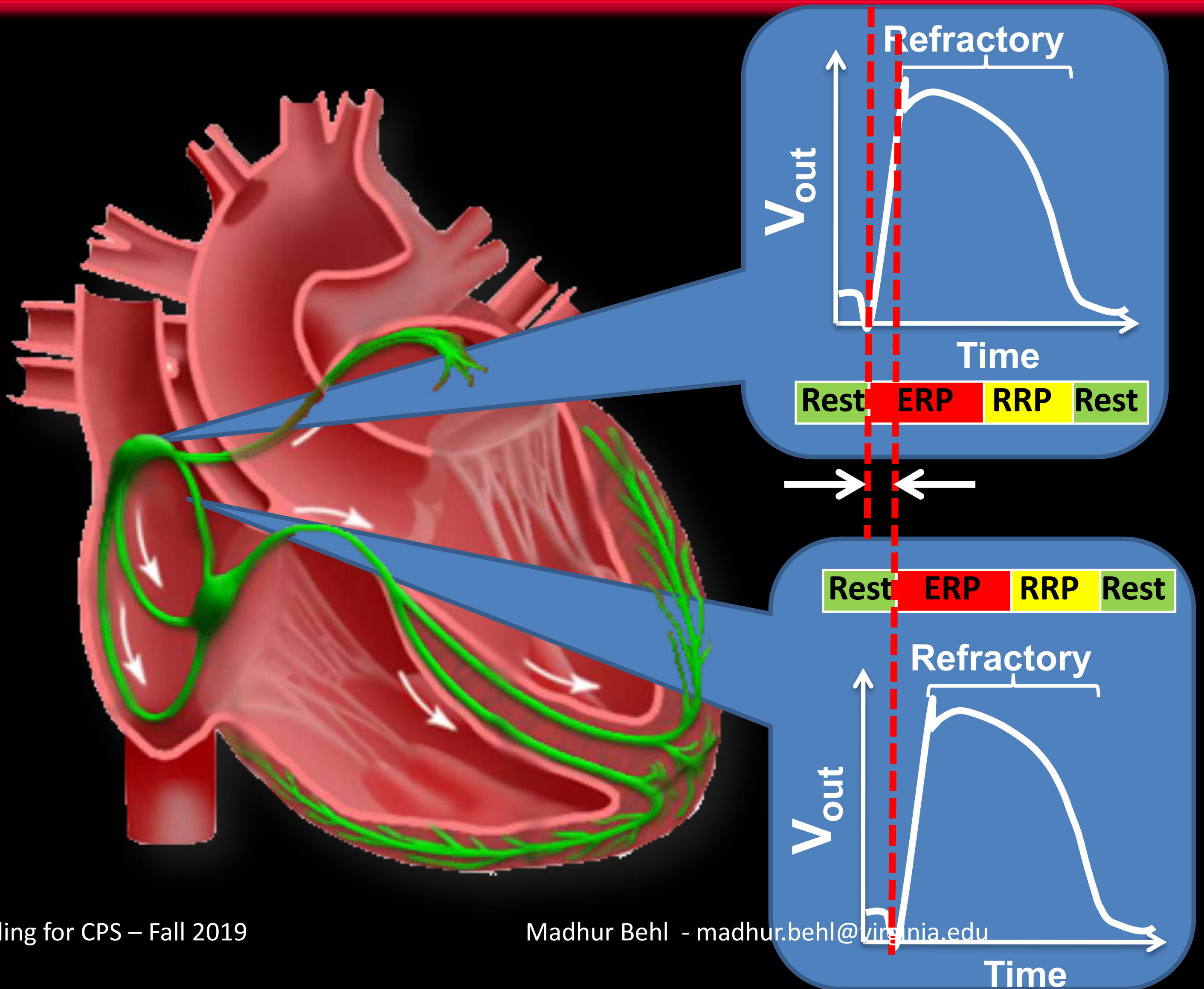
Personalized Virtual Hearts Could Improve Cardiac Surgery

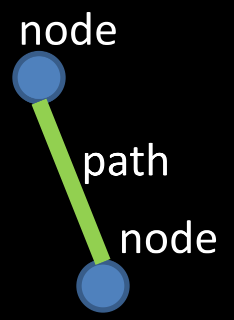
Digital replicas of patients' hearts can identify hidden, irregular heart tissue for surgeons to destroy

By **Megan Scudellari**

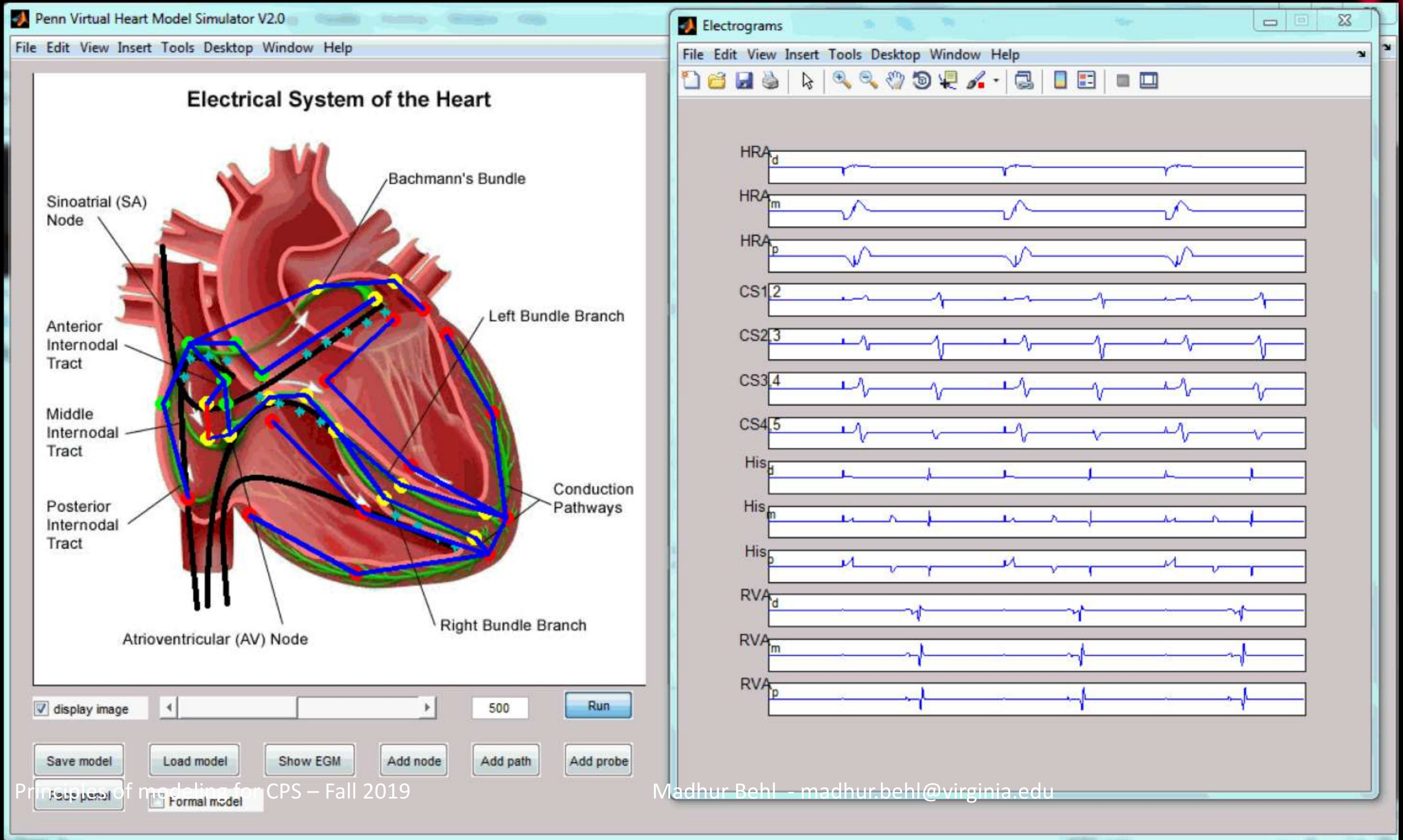


Heart Modeling



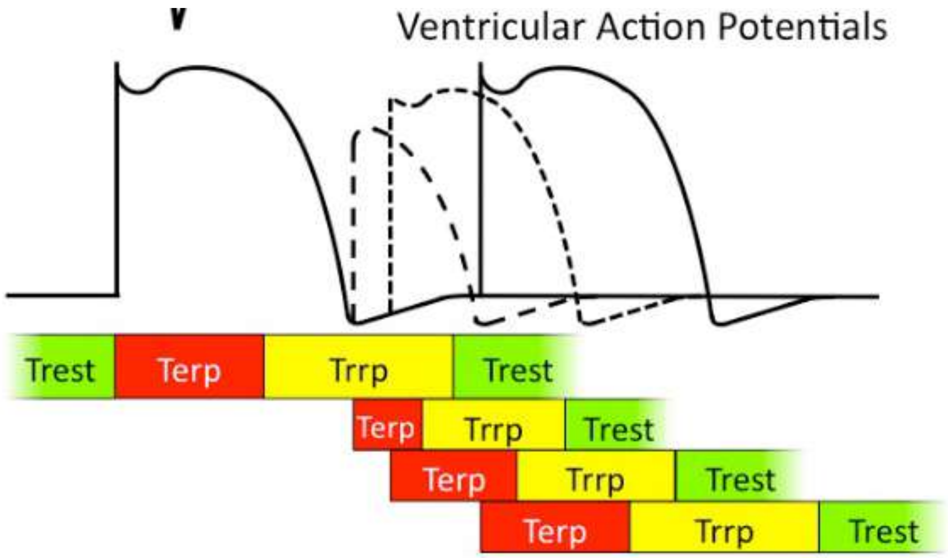


Closed-loop Heart Modeling

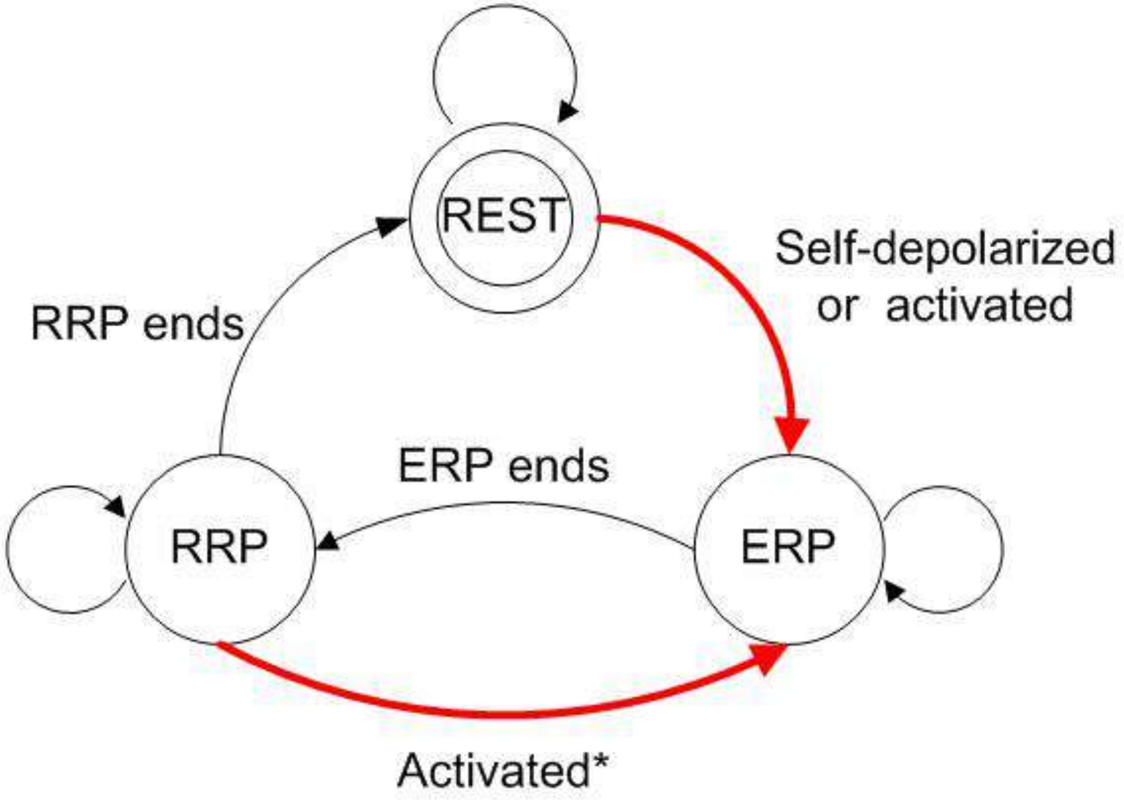


Node Automaton

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

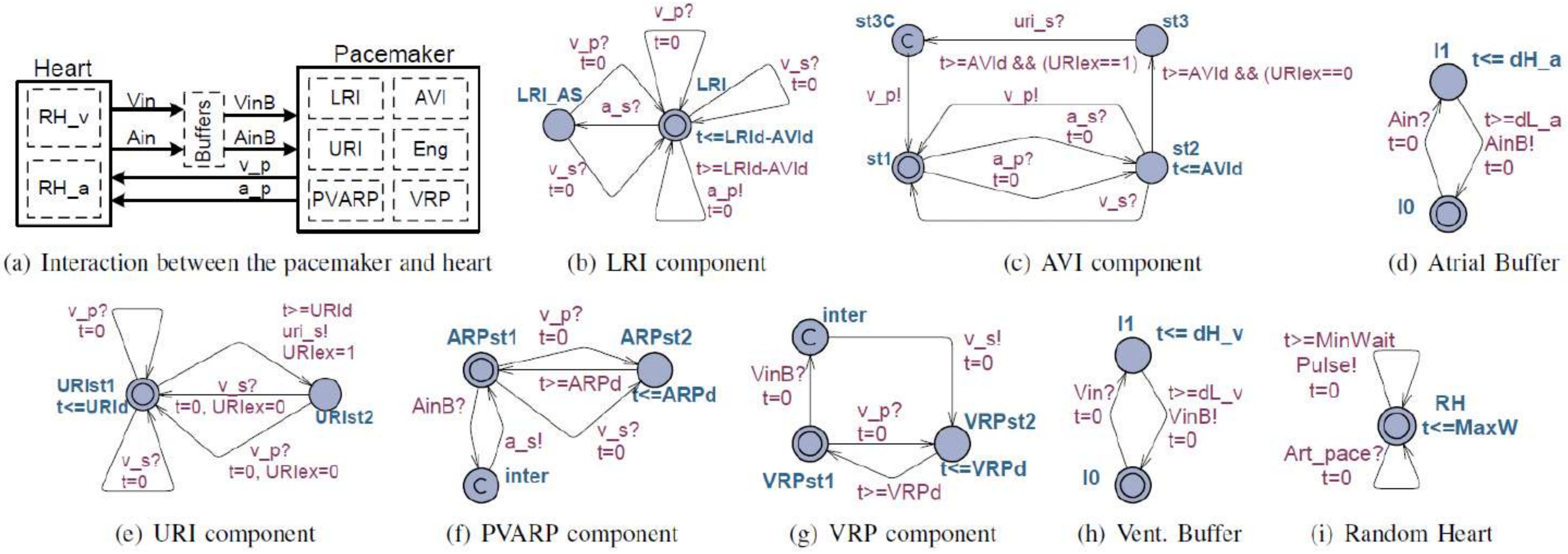


Node Automaton



* 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

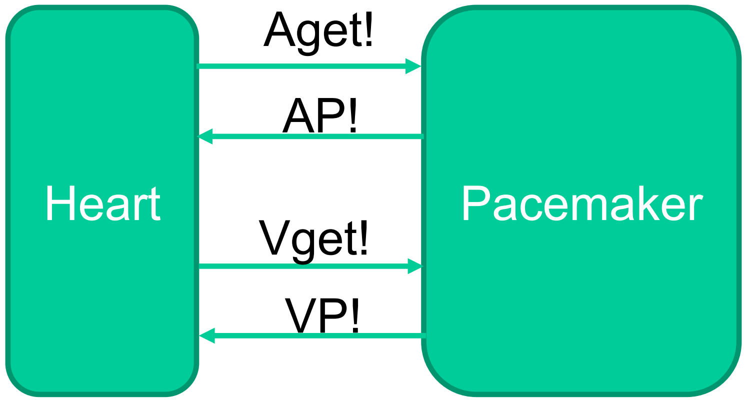
(e) URI component (f) PVARP component (g) VRP component (h) Vent. Buffer (i) Random Heart

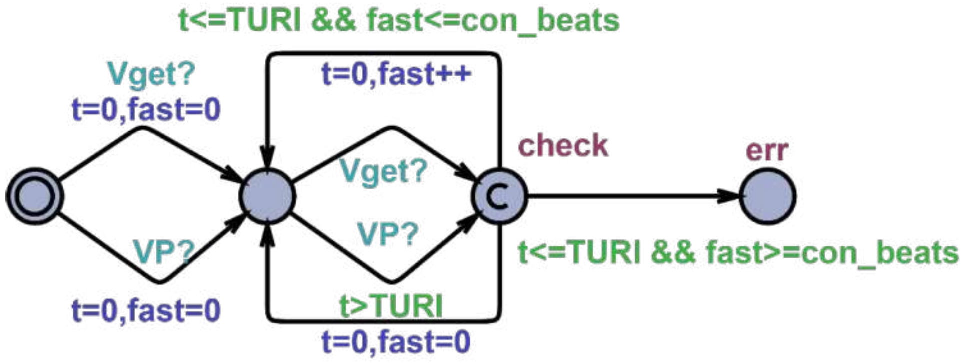
Model checking – Counter example guided.

Safety property

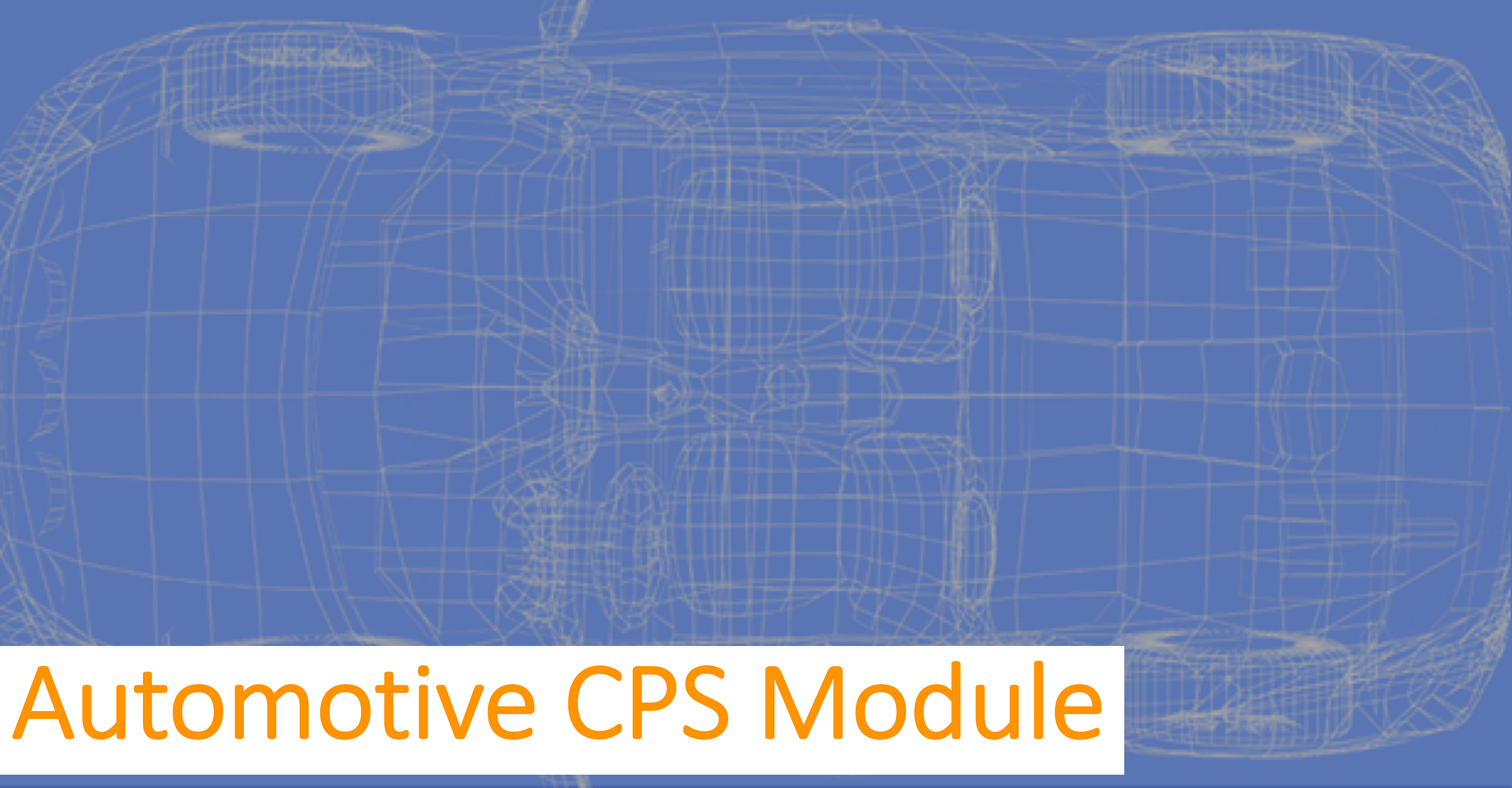
Ventricular rate should not be equal or above the upper rate limit for more than 30 beats

$$A[]not\ monitor.err$$





monitor



Automotive CPS Module

Localization and Mapping

Where am I ?

Scene Understanding

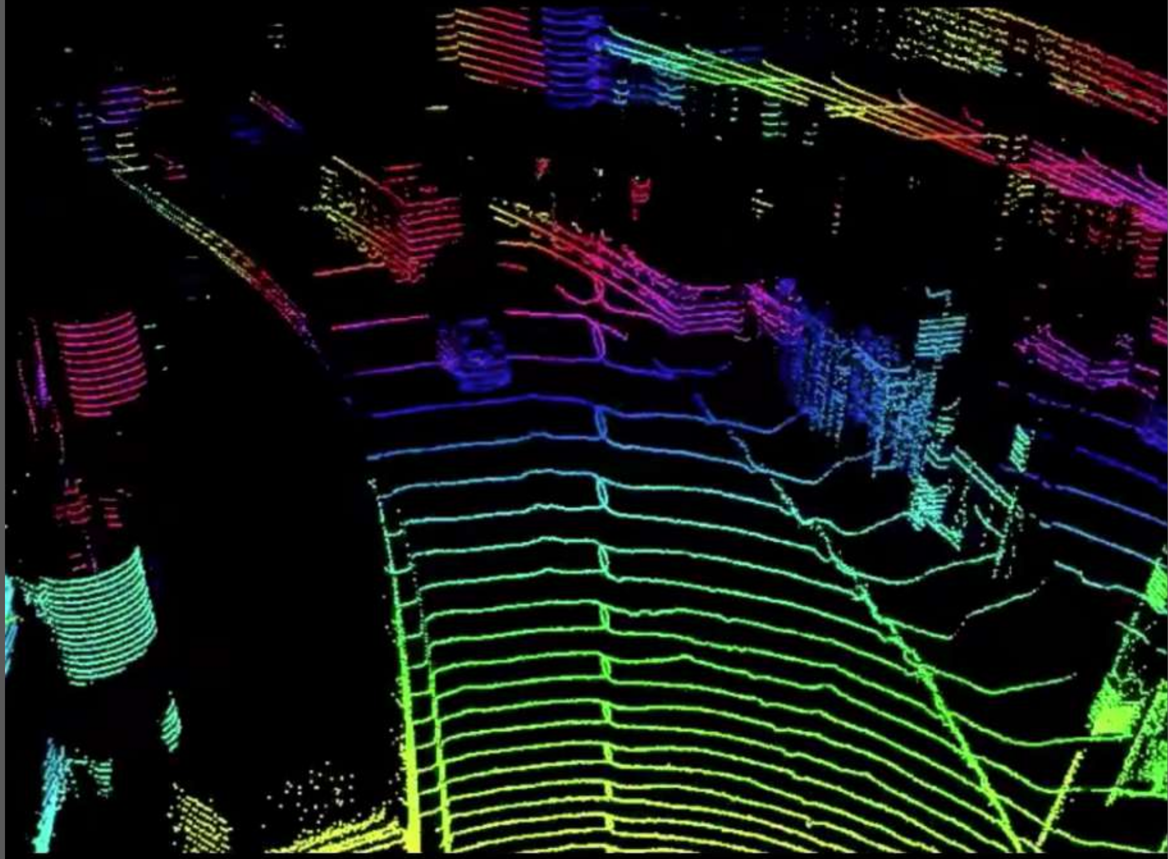
Where/who/what/why of
everyone/everything else ?

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 ?

Scene Understanding

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

Deep Learning

Trajectory Planning and Control

Where should I go next ?
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Human Interaction

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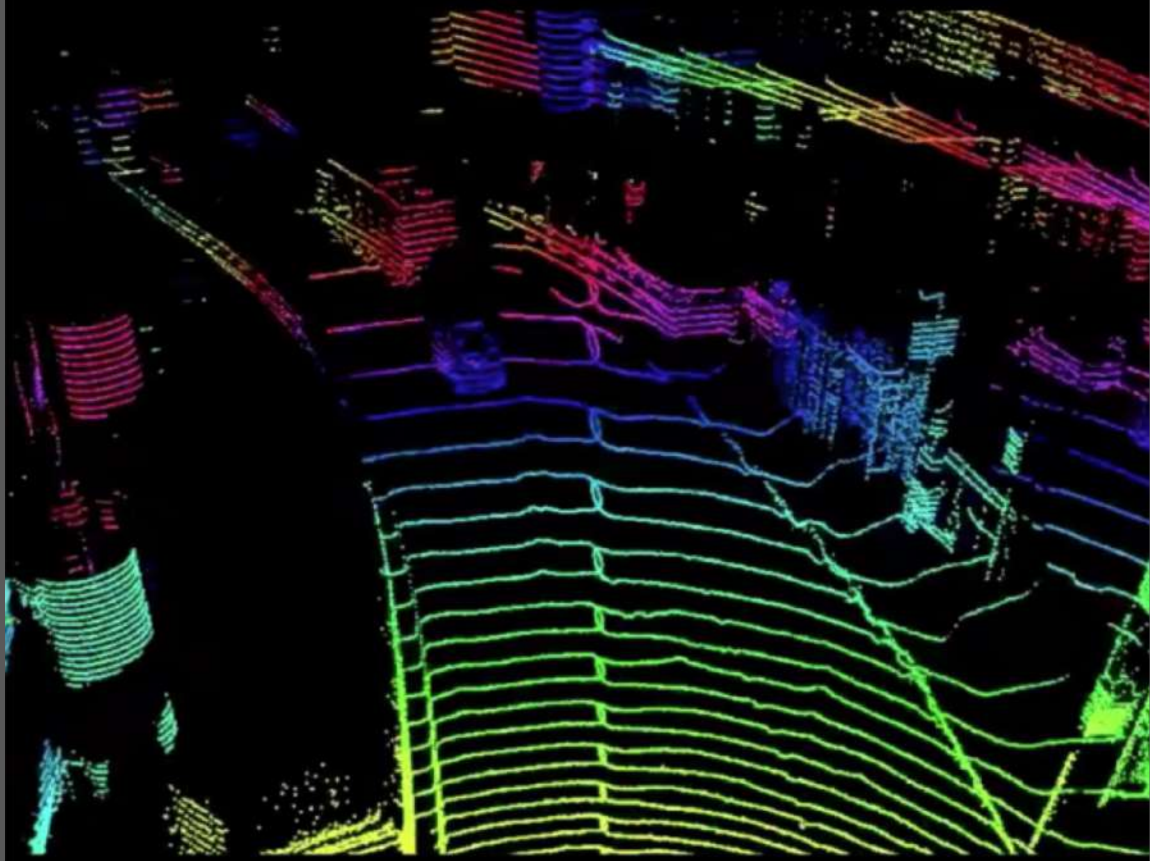


Localization and Mapping

Where am I ?

Scene Understanding

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

Deep Neural Networks

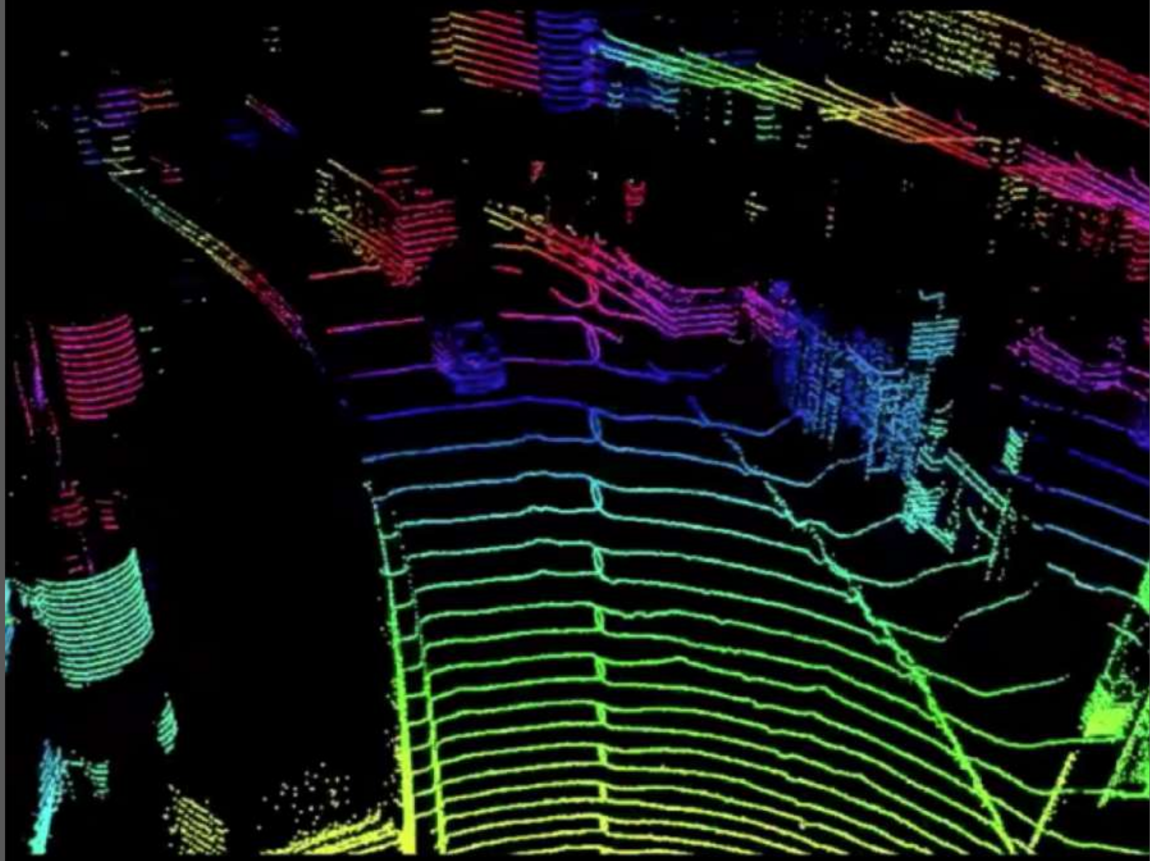
Trajectory Planning and Control

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

End-to-end learnable

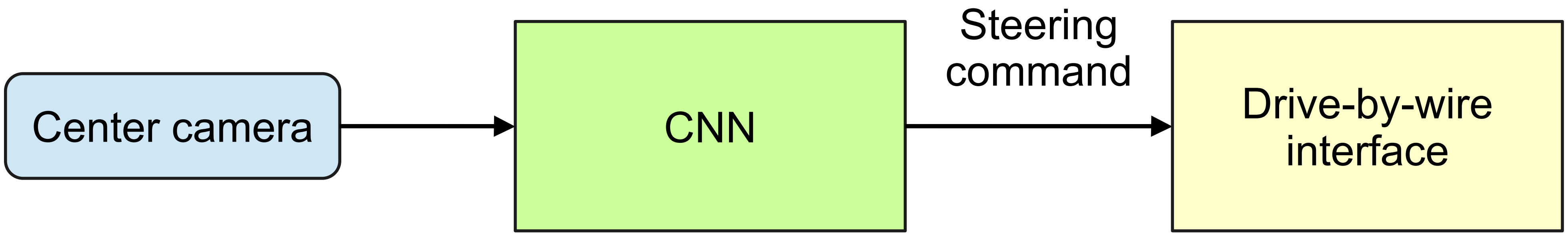
Human Interaction

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



End-to-End Deep Learning for Self Driving Cars

- NVIDIA



Video credit: DeepTesla

Machine intelligence is largely about training data.

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

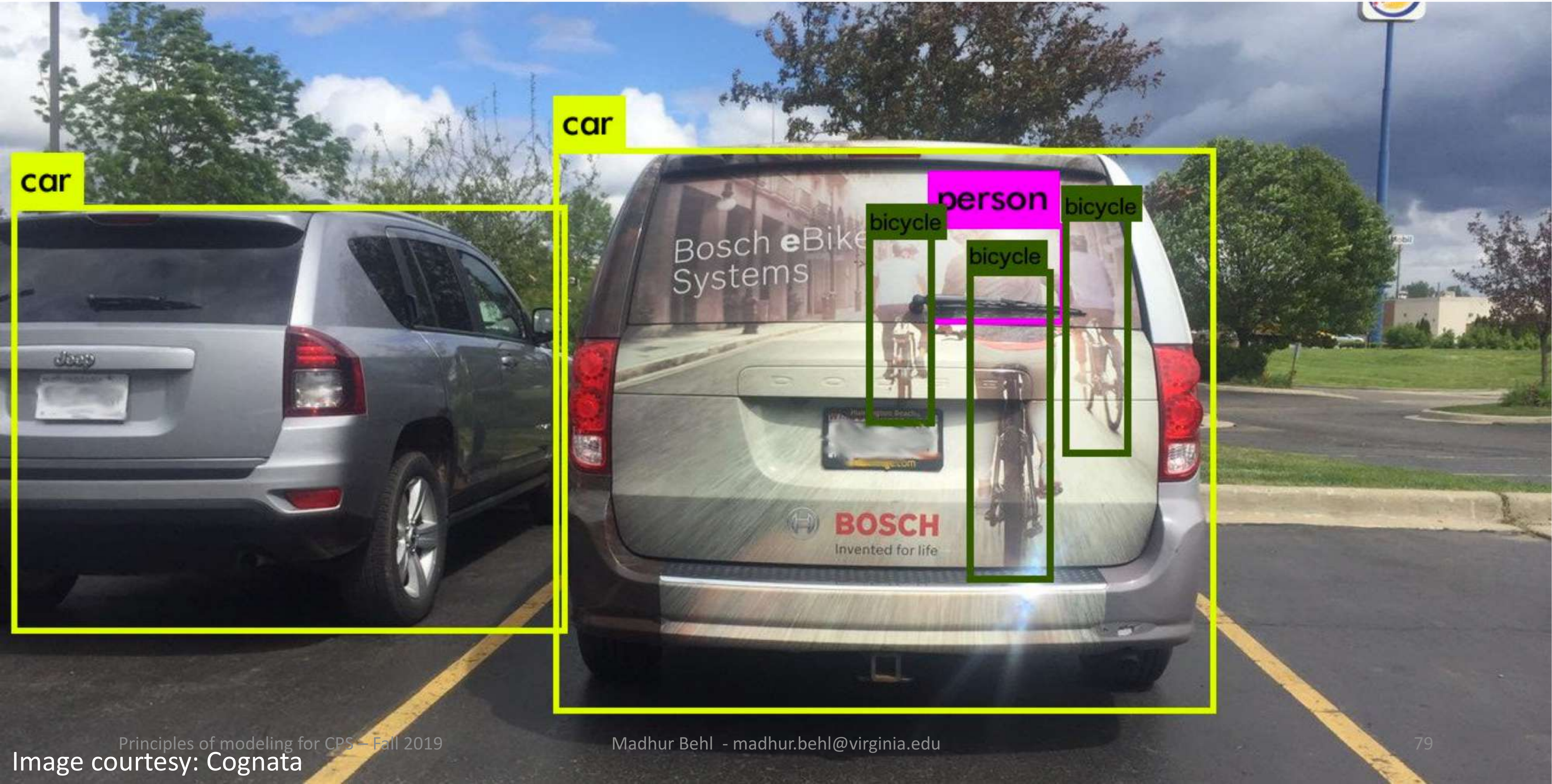


Image courtesy: Cognata

One car ? or Multiple cars ?

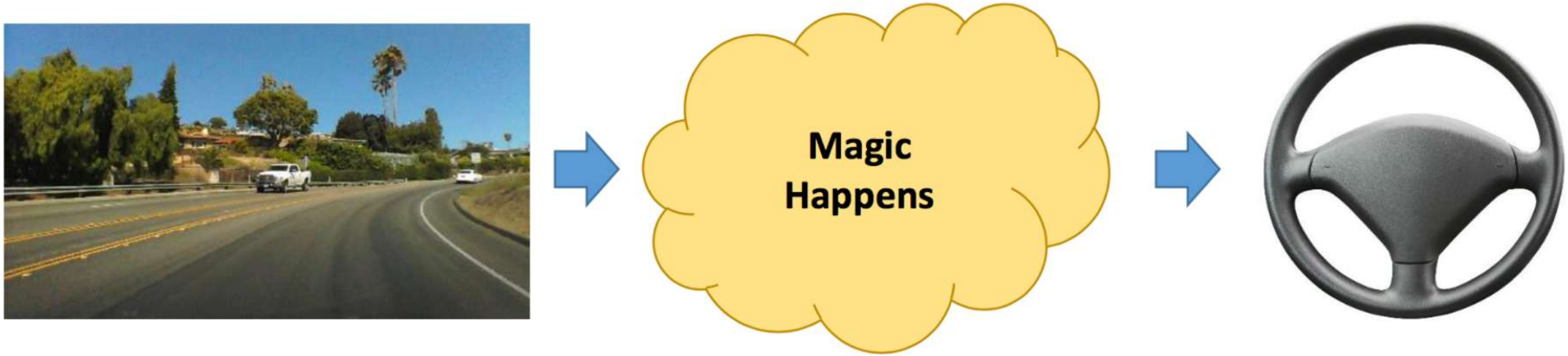
Ramen Noodle place or Do Not Enter Sign ?


下鳥羽城ノ越町
20m
MENU
現在地
AUDIO
今日
明日
16:10
12/5
9/3
60
40
12°C
A 77.5km
000160km
x1000 r/min
km/h


今日
明日
16:10
12/5
60
9/3
40
12℃
A 77.5km
000160 km
50

There is a bus right next to you!!

Autonomous Driving: End-to-End



Autonomous Driving: End-to-End

End to End Learning for Self-Driving Cars

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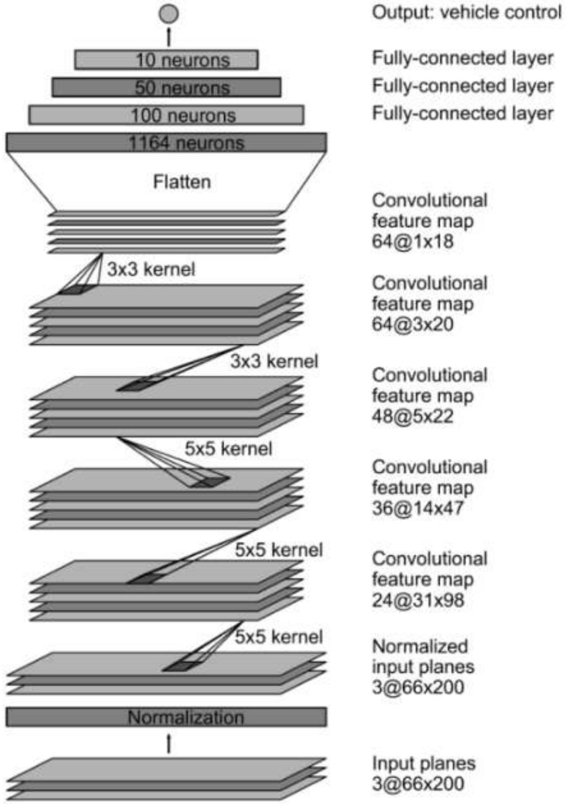
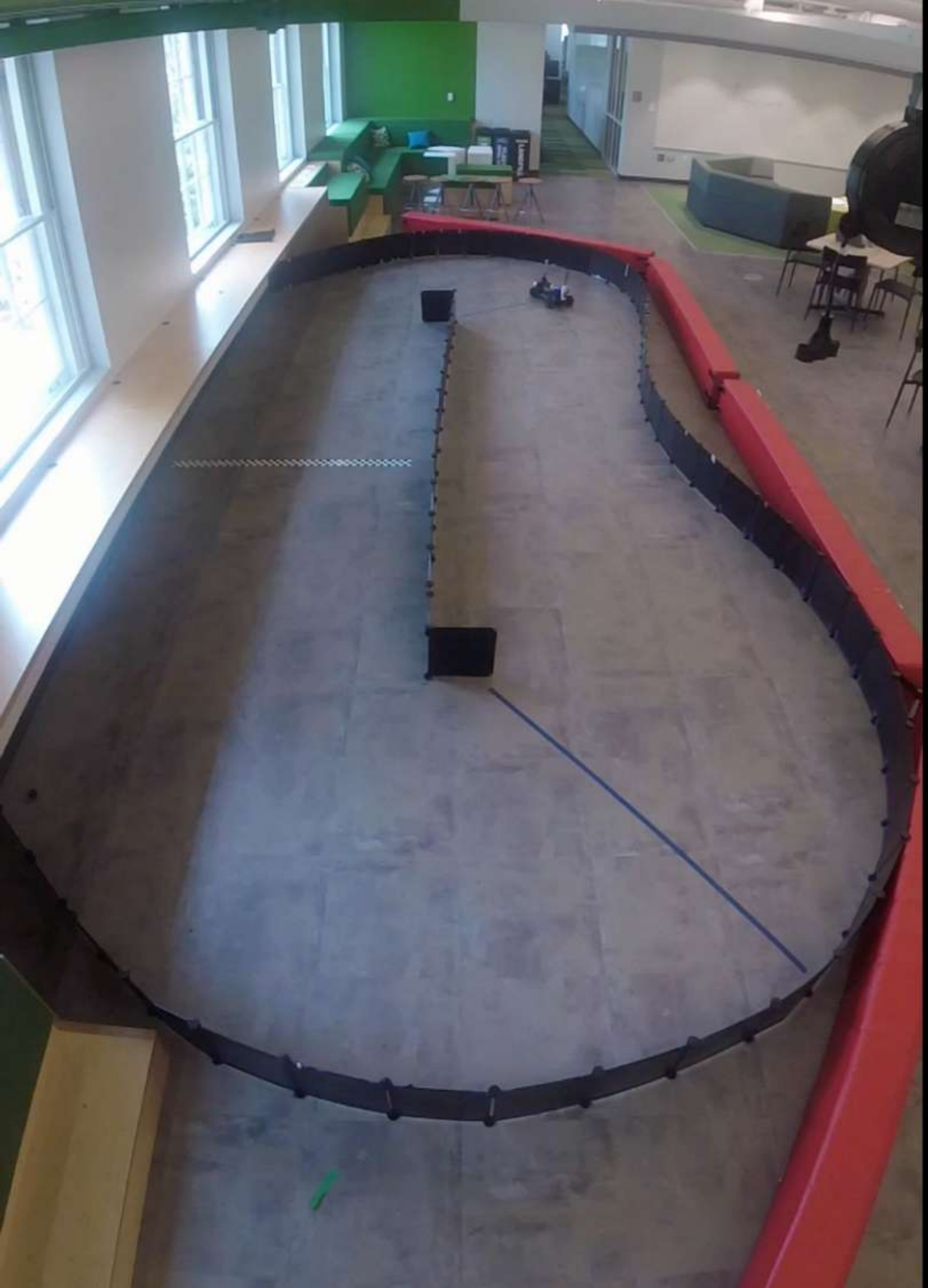
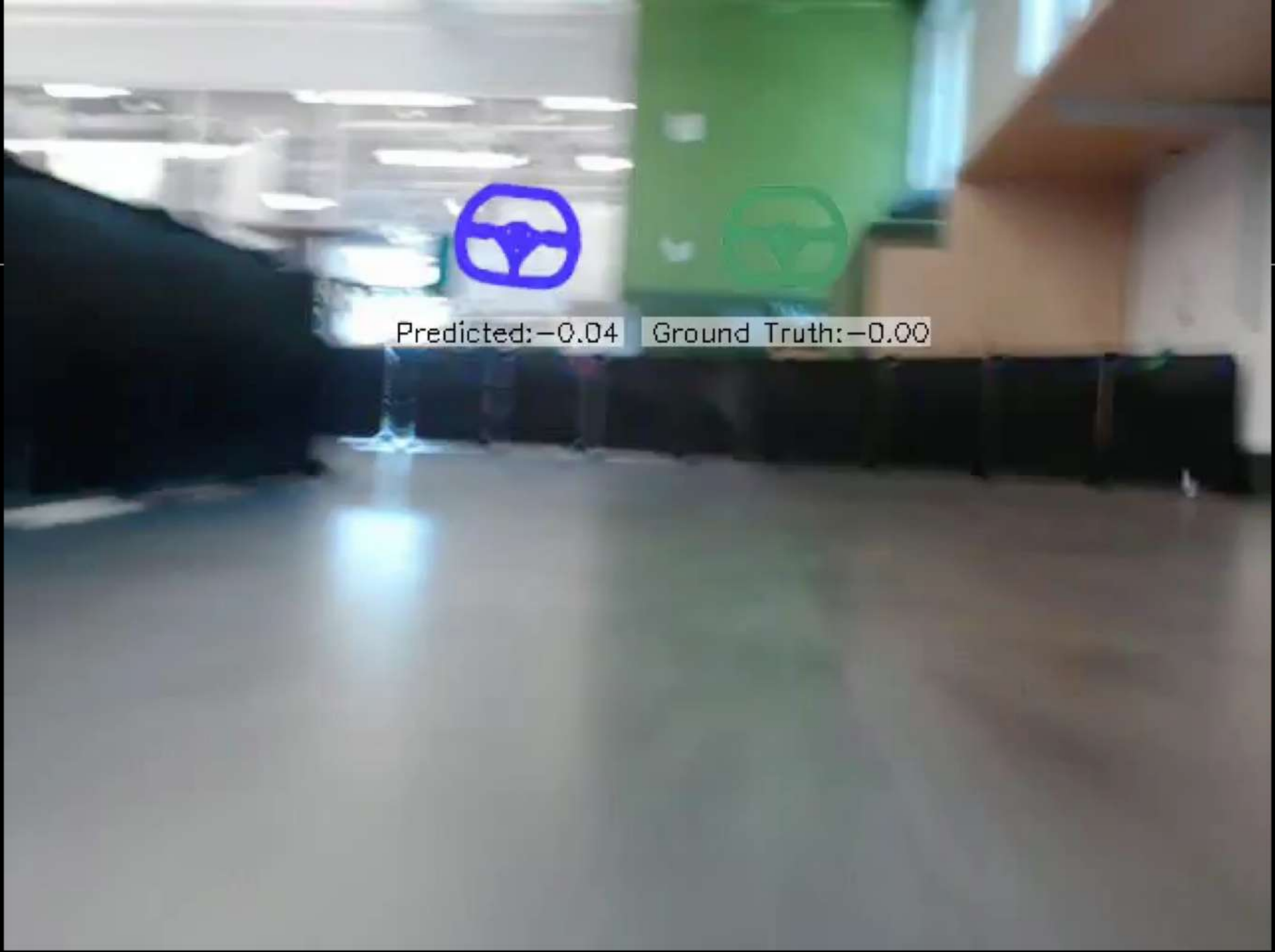
Autonomous Driving: End-to-End





F1/10
FPV
Driving


Predicted:-0.04
Ground Truth:-0.00

what is this course about ?

Principles of Modeling for Cyber-Physical Systems

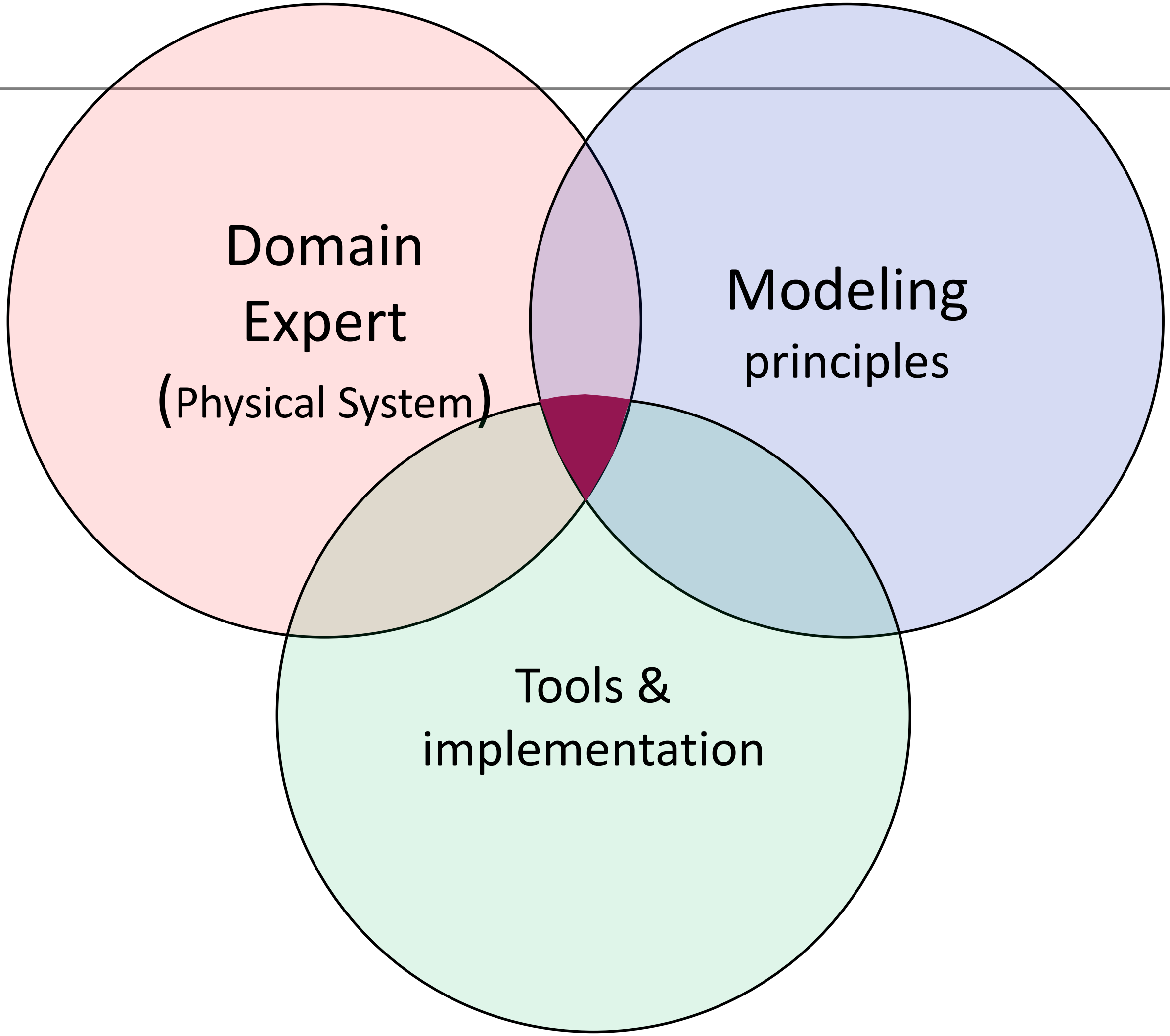
Lets break it down..

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

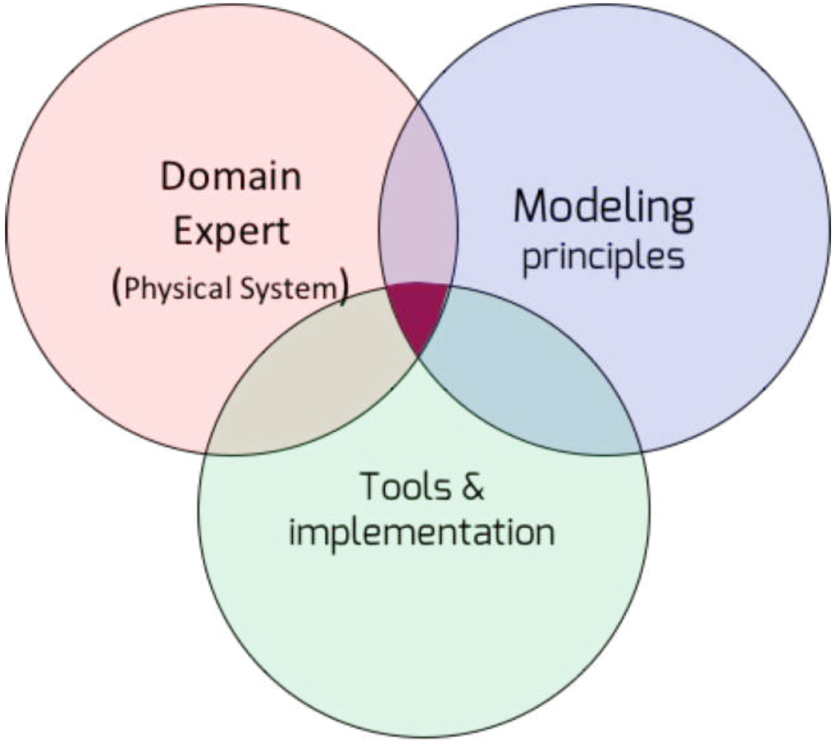
This course: Modeling principles

- 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

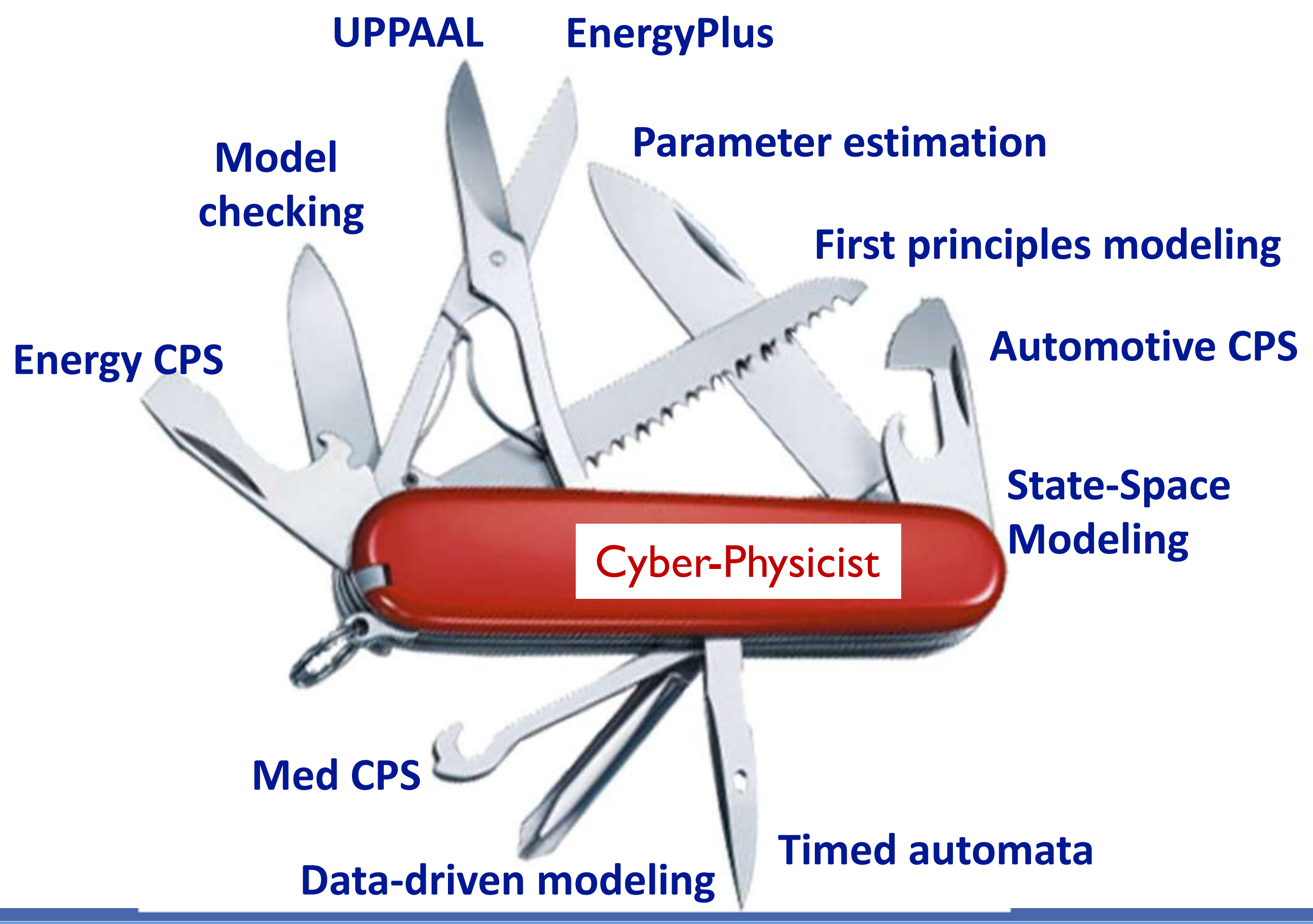


This course: Learning objectives



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

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