# Cyber Physical System



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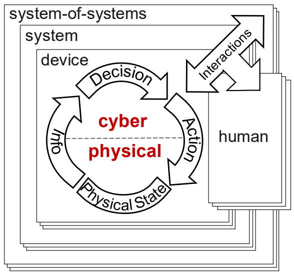
## Cyber-Physical Systems




- Examples include a smart gird, a self-driving car, a smart manufacturing plant, an intelligent transportation system, a smart city, and Internet of Things (IoT) instances connecting new devices for new data streams and new applications.
- Common notions of IoT have emphasized networked sensors providing data streams to applications.
- CPS concepts complete these IoT notions, providing the means for conceptualizing, realizing and assuring all aspects of the composed systems of which sensors and data streams are components.

***The Framework for Cyber-Physical Systems*** was released by the NIST CPSPWG on May 26, 2016



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Segway Scooter

Smart Spoon



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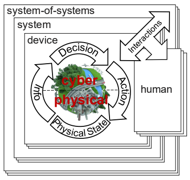
## CPS

**Cyber-Physical Systems (CPS)** comprise interacting digital, analog, physical, and human components engineered for function through integrated physics and logic.

**Examples of a CPS that are not instances of IoT**

- Segway Scooter
- **Smart Spoon** enabling Parkinson's patients to feed themselves (see https://www.liftware.com/)
- Autonomous vehicle operating without wired or wireless connections outside the vehicle, e.g.
  - a Mars rover operating between messages from Earth
  - the original vehicles in the first DARPA Challenge
  - cruise missile/smart bomb in flight to target
- Generally, any CPS that is fully contained **with no outside network connections**






https://www.amazon.com/stores/Segway/Self-BalancingScooter/page/2CA010D3-140D-4F26-96A8-2100441B4CC7

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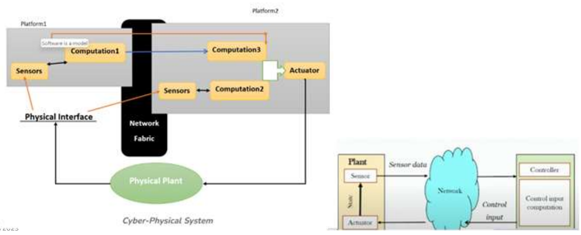
## CPS

The term "cyber-physical systems" emerged in 2006, coined by Helen Gill at the National Science Foundation in the US.



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## Definition of CPS

- Cyber-physical systems (CPS) are engineered systems that are built from, and depend upon, the seamless **integration of computation communication, control into physical components.**
- Advances in CPS will enable **capability, adaptability, scalability, resiliency, safety, security, and usability** that will expand the horizons of these critical systems.
- CPS technologies are transforming the **way people interact with engineered systems**, just as the Internet has transformed the way people interact with information.



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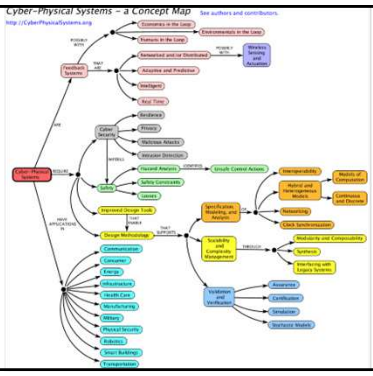




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## Application domains : Transportation

Faster, safer, more energy-efficient air travel

Improved use of airspace

Autonomous unmanned drones



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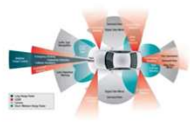
## Application domains : Transportation



Safety, security, and control of autonomous cars

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

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## Application domains : Energy

- Smart buildings.
- Energy- efficient operation.

- Smart homes.
- EV charging/ solar rooftops

- Reliable and resilient electricity grid.
- Micro grids.



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## 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 health management systems.



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## Application domains : Critical Infrastructure

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

Structural health monitoring

Utility infrastructure – Gas, Electricity, Steam.



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## Application domains : … any many more

Smart agriculture

Smart Manufacturing

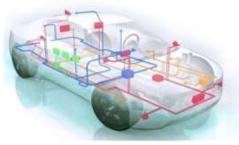
Industrial control

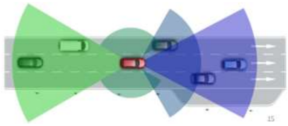




## Automotive CPS

- Safer Transportation
- Reduced Emissions
- Smart Transportation
- Energy Efficiency
- Climate Change
- Human-Robot Collaboration









## 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**

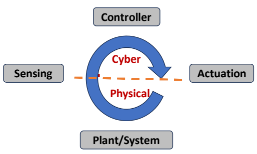
**Fusion of physical and computational sciences**

**Produce significant impact on society**





**Closing the loop**




Human in loop





## 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
- Conventional and unconventional substrates/platforms

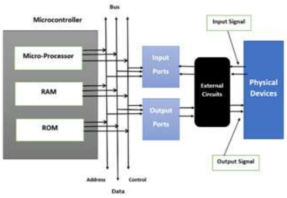
## Embedded system

A computer system integrated into a device to perform a dedicated function, often part of a larger system.

•**Key Components:** Microcontroller/Microprocessor, Sensors, Actuators, I/O Interfaces.

•**Features:**

- •Application-specific, optimized design
- •Real-time performance requirements
- •Power-efficient and reliable



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## CPS) vs Embedded System

| Aspect | CPS | Embedded System |
|---|---|---|
| **Definition** | Integration of physical processes with cyber components | Software-hardware combination built into a device |
| **Purpose** | Monitors and controls physical processes seamlessly | Designed for a specific, dedicated function |
| **Flexibility** | Adaptable to changes in the physical environment | Less flexible, focused on a specific task |
| **Complexity** | Used in complex, interconnected systems | Used in standalone devices like appliances and gadgets |
| **Programming Languages** | High-level languages (e.g., Python, Java) | Low-level languages (e.g., C, Assembly) |



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## CPS) vs Embedded System

| Aspect | CPS | Embedded System |
|---|---|---|
| **Interaction** | Direct interaction with and control of physical processes | Limited interaction, task-specific control |
| **Key Components** | Sensors, actuators, control systems, networks, computing devices | Microcontrollers, sensors, communication modules, memory |
| **Power Consumption** | Higher due to system complexity | Lower, optimized for energy efficiency |
| **Cost** | More expensive to develop and maintain | Generally cost-effective |
| **Examples** | Smart homes, industrial control systems, wearable devices | Home appliances, medical devices, consumer electronics |



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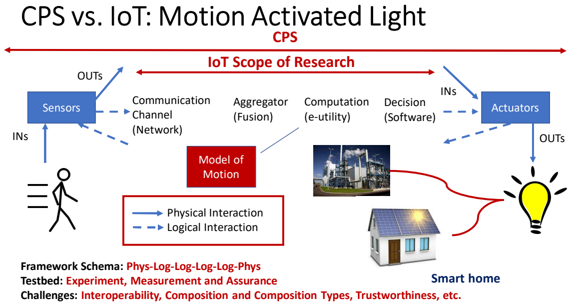
## CPS vs. IoT: Motion Activated Light



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## Contradiction in CPS

- High connectivity vs. Security and Privacy
- Adaptability vs. Repeatability
- High performance vs. Low Energy
- Asynchrony vs. Coordination/Cooperation
- Scalability vs. Reliability and Predictability
- Laws and Regulations vs. Technical Possibilities
- Economies of scale (cloud) vs. Locality (fog)
- Open vs. Proprietary
- Algorithms vs. Dynamics



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## Challenges of Working in a Multidisciplinary Area




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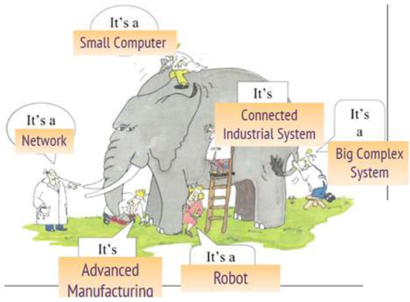


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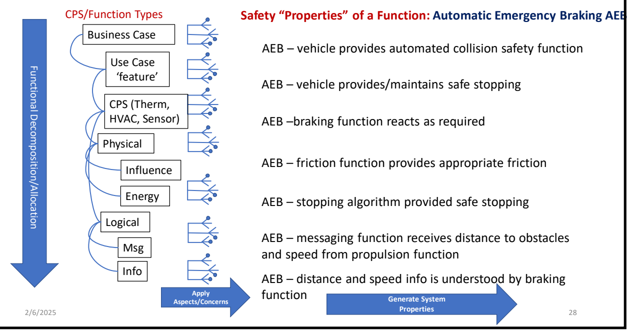
## Applying CPS Framework to Decomposition

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## IT- vs CPS-Based Risk Mitigation

| | Primary Impact of Failure | | Mitigation Mechanisms | | |
|---|---|---|---|---|---|
| | Digital | Physical | Digital | Analog | Physical |
| IT System | ✓ | | ✓ | | |
| IoT/CPS | ✓ | ✓ | ✓ | ✓ | ✓ |

*"Better cybersecurity through physics!"*

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## Tools

Enterprise Architect: UML Editor

XMLSpy: XML/XMLSchema Editor

TortoiseGit: Windows GitTool

Notepadd++: Programmers Editor

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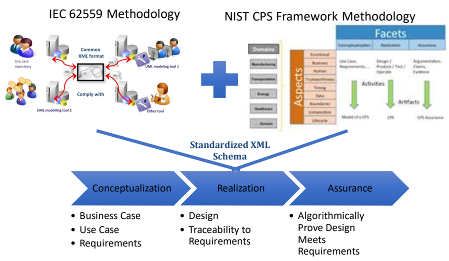
## Derivation of a Union of Technologies

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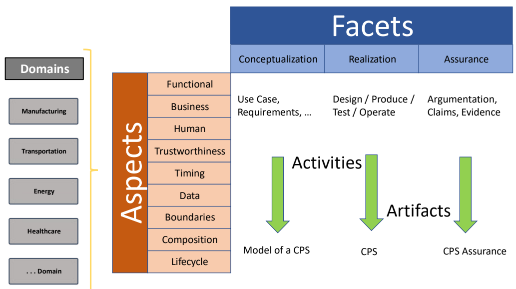
## CPS Framework

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## Why is CPS hard ?




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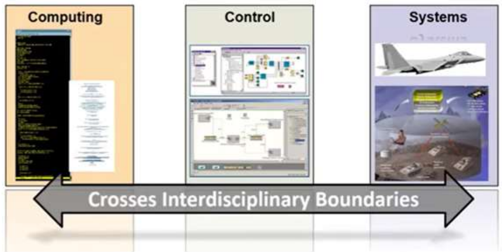
## Why is CPS hard ?



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## 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 reconstructed



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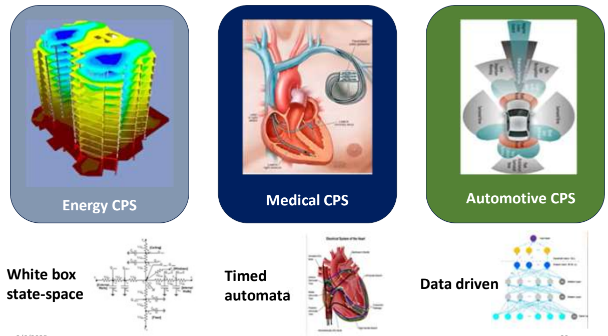




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## The control problem in buildings

**Integrated control of:**

- **Heating**
- **Cooling**
- **Ventilation**
- **Lighting**
- **Blinds**



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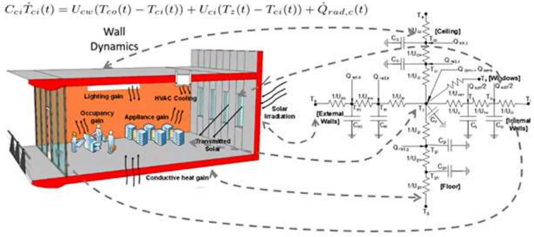
## State-space 'RC' thermal modeling

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



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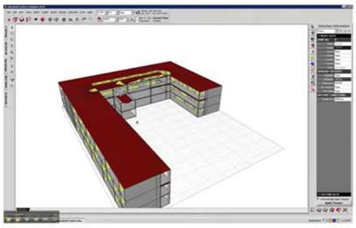
## Whole building energy simulation



Using EnergyPlus

Generating input-output data

Modeling a building in MATLAB



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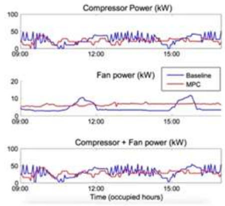
## Predictive control



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## Medical CPS: 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





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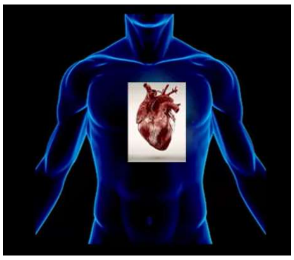
## Implantable Pacemaker



- 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



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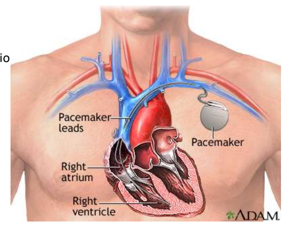
## Challenges

**Pacemaker**
- Autonomous device with minimum human interactio
- 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



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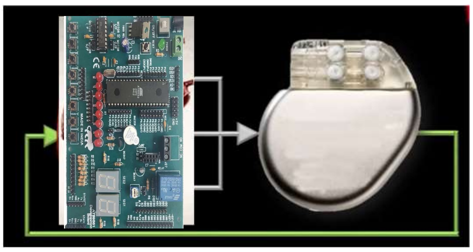
## Closed - loop evaluation





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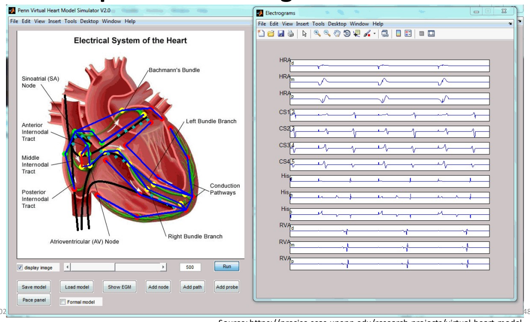
## Closed - loop heart modeling




Source: https://precise.seas.upenn.edu/research-projects/virtual-heart-model



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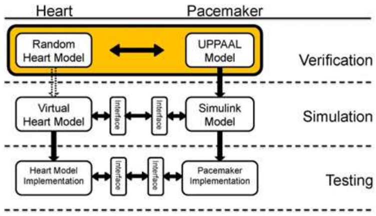
## Closed - loop heart modeling




Source: https://precise.seas.upenn.edu/research-projects/virtual-heart-model



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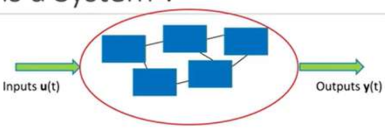
## What is a System ?




Mapping from time dependent inputs to time dependent outputs

(causal definition)



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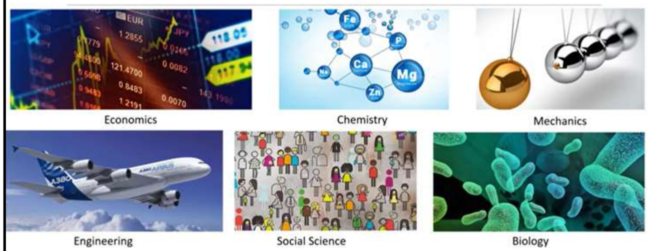
## Differential equations

Many phenomena can be expressed by equations which involve the **rates of change** of quantities (position, population, concentraition, temperature...) that describe the **state** of the phenomena.



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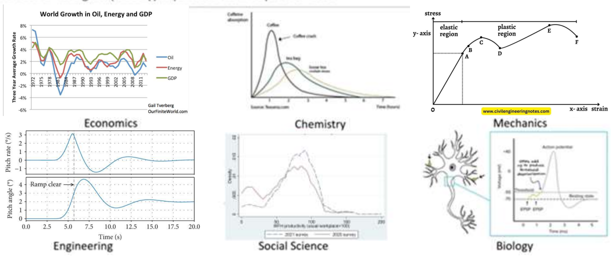
## Differential equations

The state of the system is characterized by **state variables**, which describe the system.

The rate of change is (usually) expressed with respect to time



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## Modling type: Physical Modeling



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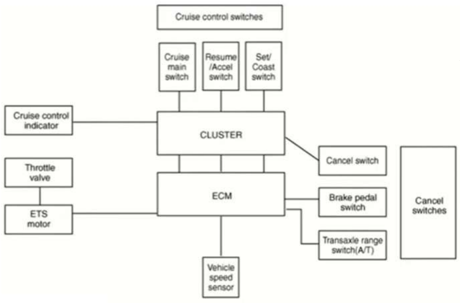
## Modeling types: Functional/compositional modeling




Do you know of any tools for functional modeling?

Unified Modeling Language



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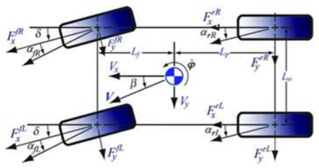
## Modeling types: Mathematical modeling



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

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

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



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## Modeling types: Computational modeling




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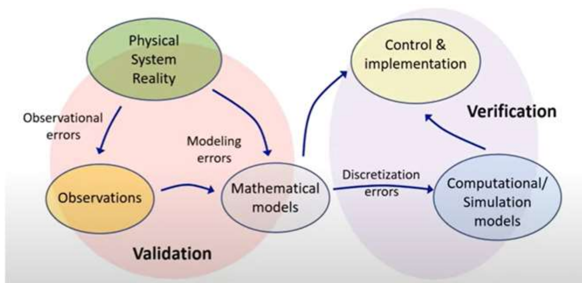
## About mathematical models



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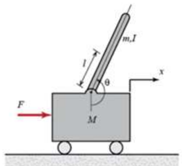
## Inverted Pendulam Problem




[redacted]

- Inverted pendulum mounted to a motorized cart.
- Unstable without control :
  - pendulum will simply fall over if the cart isn't moved to balance it.

Balance the inverted pendulum by applying a force to the cart on which the pendulum is attached.



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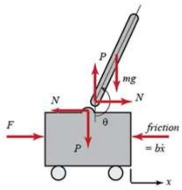
## Inverted pendulum – ODEs




Forces in the horizontal direction $M\ddot{x} + b\dot{x} + N = F$

Reaction force N: $N = m\ddot{x} + ml\ddot{\theta}\cos\theta - ml^2\dot{\theta}^2\sin\theta$

Governing equation (1) of this system: Horizontal

$$(M + m)\ddot{x} + b\dot{x} + ml\ddot{\theta}\cos\theta - ml^2\dot{\theta}^2\sin\theta = F$$

Forces in the vertical direction:

$$P\sin\theta + N\cos\theta - mg\sin\theta = ml\ddot{\theta} + m\ddot{x}\cos\theta$$

Get rid of the P and the N terms: (moment balance equation) $-Pl\sin\theta - Nl\cos\theta = I\ddot{\theta}$

Governing equation (2) of this system: Vertical

$$(I + ml^2)\ddot{\theta} + mgl\sin\theta = -ml\ddot{x}\cos\theta$$



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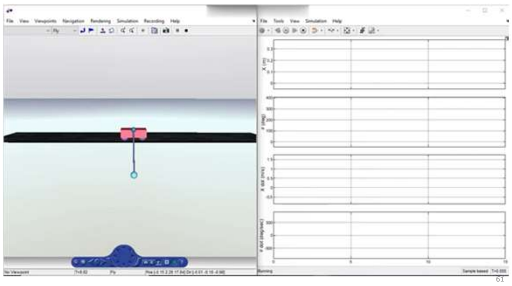
## Matlab simulation





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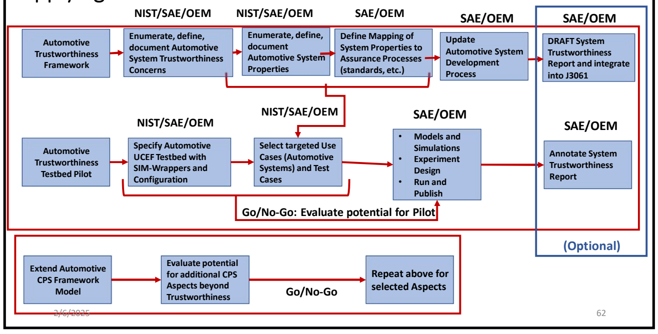
## Applying CPS Framework to Autonomous Vehicles



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## Automative CPS

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 ?
How do I steer and accelerate ?

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



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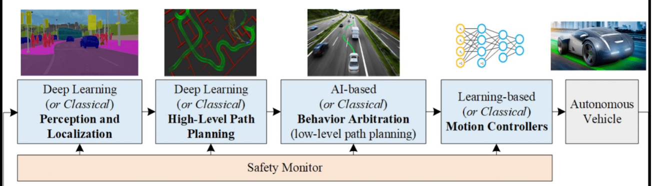
## Automative CPS






Source: https://neptune.ai/blog/self-driving-cars-with-convolutional-neural-networks-cnn



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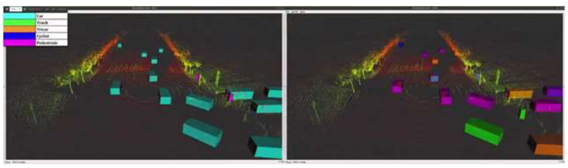
## Automative CPS **LiDAR**

Light Detection And Ranging





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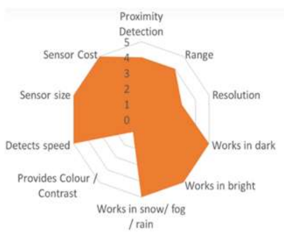
## Radar



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## Localization



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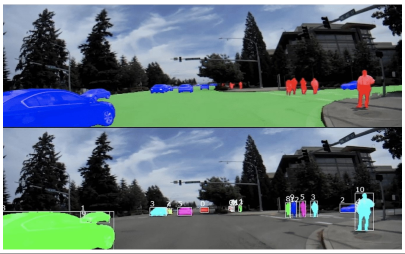
## Localization

- Visual based deep learning





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## CPS as Functors

A cyber-physical system, in the sense of process algebra, can be represented as a **functor from a symmetric monoidal category to the category CyPhy.**

Such a functor represents:

- Processes as instances of **Sensing, Decision, Action or Physical**
- Interactions as **exchanges of information or exchanges of energy**

Benefit of this representation can be derived from:

- Structural representation of one CPS 'in another' (isomorphic with a *sub-CPS*)



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