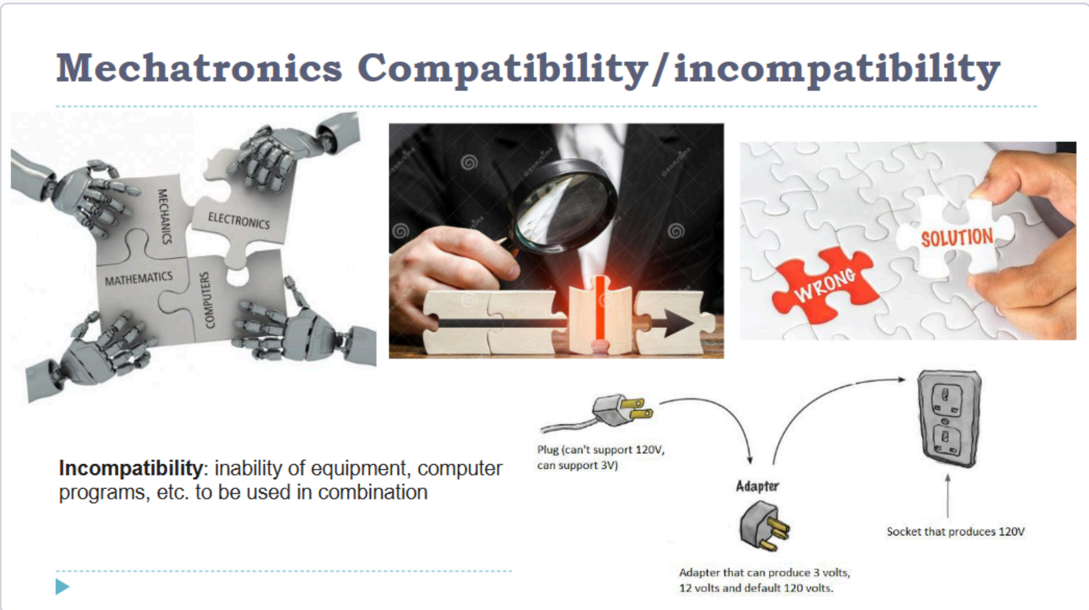
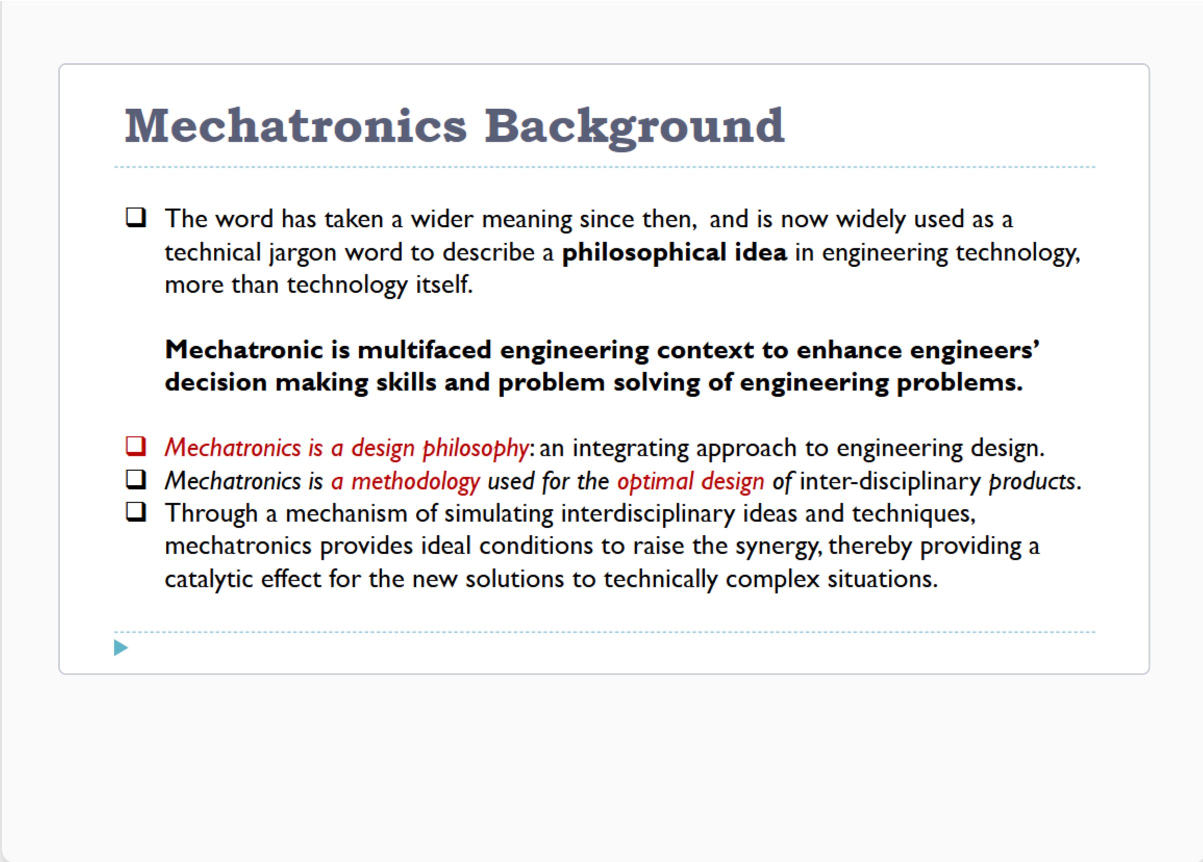
Lecture 1 - Mechatronic System Design Principles

Mechatronics and Synergy

- System view and big picture are important for ensuring an integrated, optimized, and compatible design

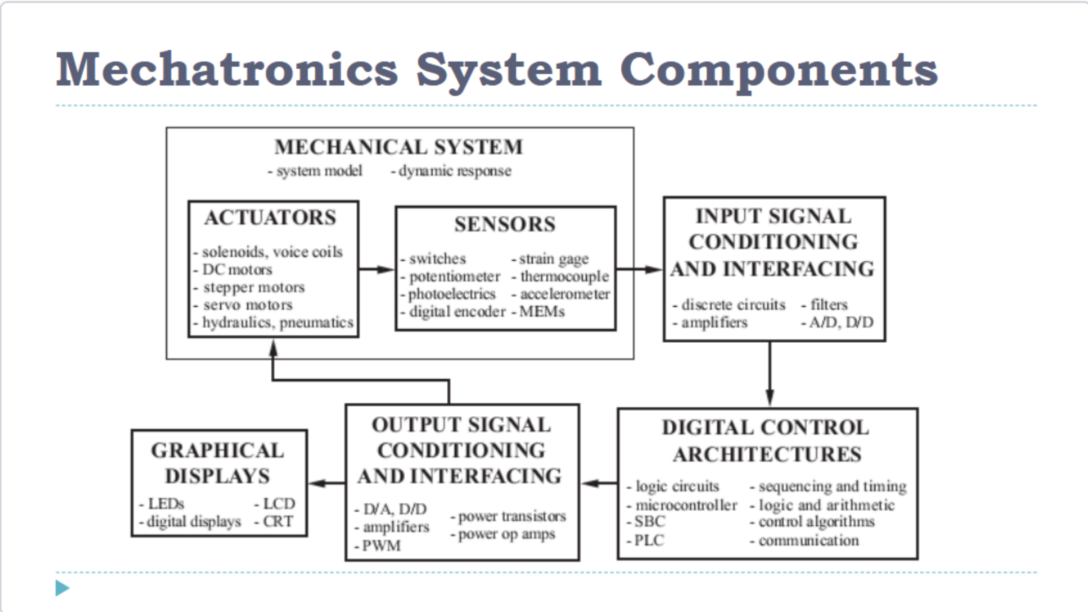
- Mechatronics is a philosophy and an engineering framework for tackling interdisciplinary problems



Mechatronic Systems Design Process

- Mechatronic system design process is as follows: problem -> requirements -> conceptual design (layout/block diagram) -> mathematical modeling and simulation (design) -> optimization -> prototyping -> deployment
- Optimization occurs when the requirements are translated into a performance index that allows for comparing multiple solutions
- Mechatronics system components. This is a layout/block diagram that is used to

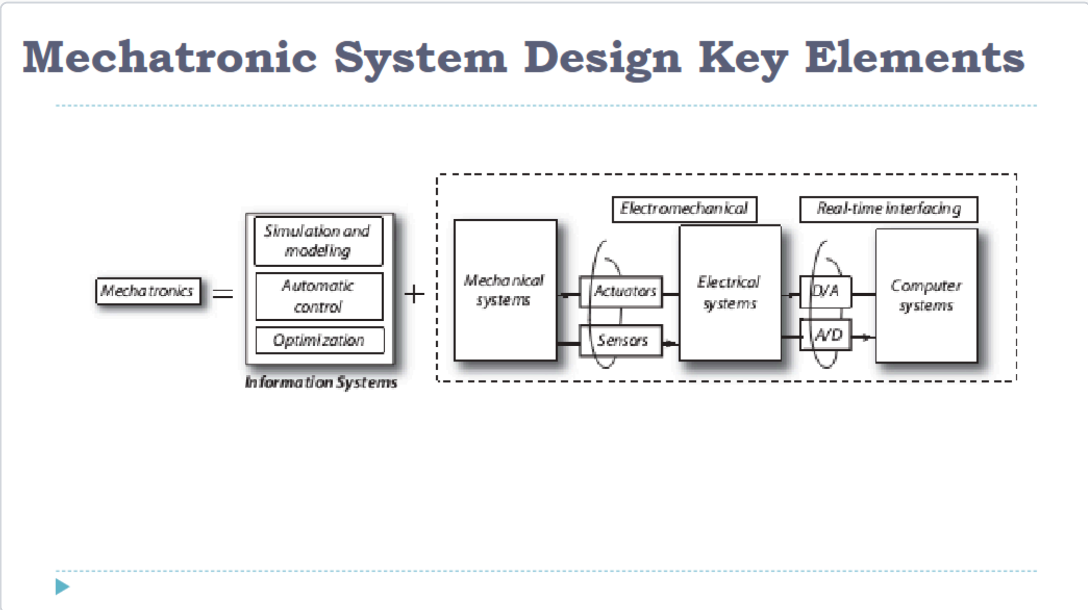
determine the initial conceptual solution for satisfying the requirements for solving a problem



- Strain gauge measures strain, not force. Strain, calculated due to change in resistance, is used for calculating stress
- EEG and EMG sensor signals are in micro volts. They must be amplified to be sensed by the controller
- Drivers and interfacing components are needed to allow the low power control signal

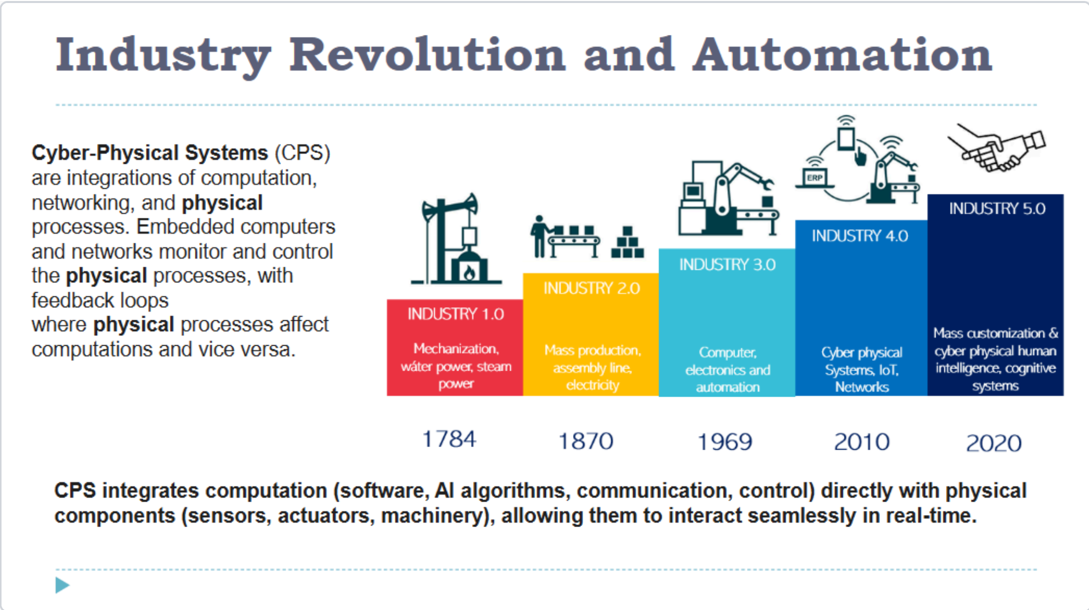
to operate a high-power actuator

- Modeling and simulation are key for engineering-based design that accelerates solutions and saves money. It can be also used for control



Industrial Revolutions

- What distinguishes each industrial revolution?



- 1.0: from man power to machine power
- 2.0: from steam to electricity and mass production
- 3.0: from hardware programming to computers and automation
- 4.0: real-time autonomy (machines self-monitor and take action) and connectivity (machines communicate with each other and generate data)
- 5.0: from focusing on industry to focusing on society and the environment

Industry 5.0

Highlights

✎ **It complements the existing "Industry 4.0" approach by specifically putting research and innovation at the service of the transition to a sustainable, human-centric and resilient European industry.**

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✎ **Industries can play an active role in providing solutions to challenges for society including the preservation of resources, climate change and social stability.**

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✎ **This approach to industry contributes to 3 of the Commission's priorities : "An economy that works for** people", "European Green Deal" and "Europe fit for the digital age". Elements related to the future of industry are already part of major Commission policy initiatives adopting a human-centric approach for digital technologies including artificial intelligence, up-skilling and re-skilling European workers, particularly digital skills modern, resource-efficient and sustainable industries and transition to a circular economy, a globally competitive and world-leading industry, speeding up investment in research and innovation

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These are just some examples that demonstrate the strong links between the

industrial transition and other societal developments.

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- Industry 5.0 is distinguished by this human-centric approach

Cyber-Physical Systems

- What are cyber physical systems?

Cyber-Physical Systems The Core of Indus

Highlights

The principle idea behind the implementation of Industry 4.0 solutions is to empower manufacturing companies to enhance collaboration among various departments, making the right information available to the right people on a real-time basis. The goal is to facilitate appropriate decision-making at the right time, thereby increasing efficiency and productivity.

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✎ **cyber-physical systems are smart systems that include engineered interacting networks of physical and computational components. The publication highlights that these highly interconnected and integrated systems provide new functionalities to improve quality of life and enable technological advances in critical areas, such as personalized health care, emergency response, traffic flow management, smart manufacturing, defense and homeland security, and energy supply and use.**

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✎ **Cyber-physical systems: Directly record physical data using sensors and affect physical processes using actuators**

Evaluate and save recorded data and actively or reactively interact both with the physical and digital world Are connected with one another and in global networks via digital communication facilities Use globally available data and services Have a series of dedicated, multimodal human-machine interfaces

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From a manufacturing industry perspective, a cyber-physical system is an internet-enabled physical entity, such as a pump or compressor, embedded with computers and control components consisting of sensors and actuators. Such an entity, which is IP address-assigned, is capable of self-monitoring, generating information about its own functioning, and communicating with other associated entities or

even outside. It is a self-regulating and autonomous operation.

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The tenet of Industry 4.0 is that a manufacturing company will be able to achieve higher efficiency, productivity, and the autonomous operation of production processes by ensuring that machines/plant equipment, logistics systems, work-in-progress components, and such other elements (including people) directly communicate with each other to achieve collaboration. A manufacturing company that wants to align its vision with that of Industry 4.0 must take steps to convert existing physical entities into cyber-physical systems.

> *The professor said that the collaboration between robots/machines and humans is unique to industry 5.0. This feels like going backwards. I will ask the professor and update it.*

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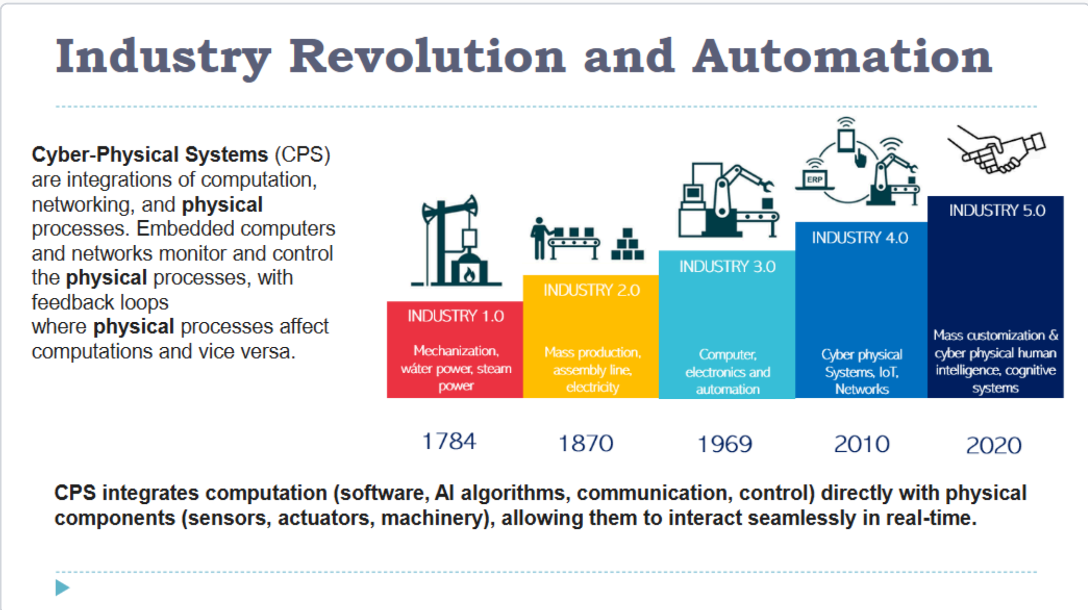
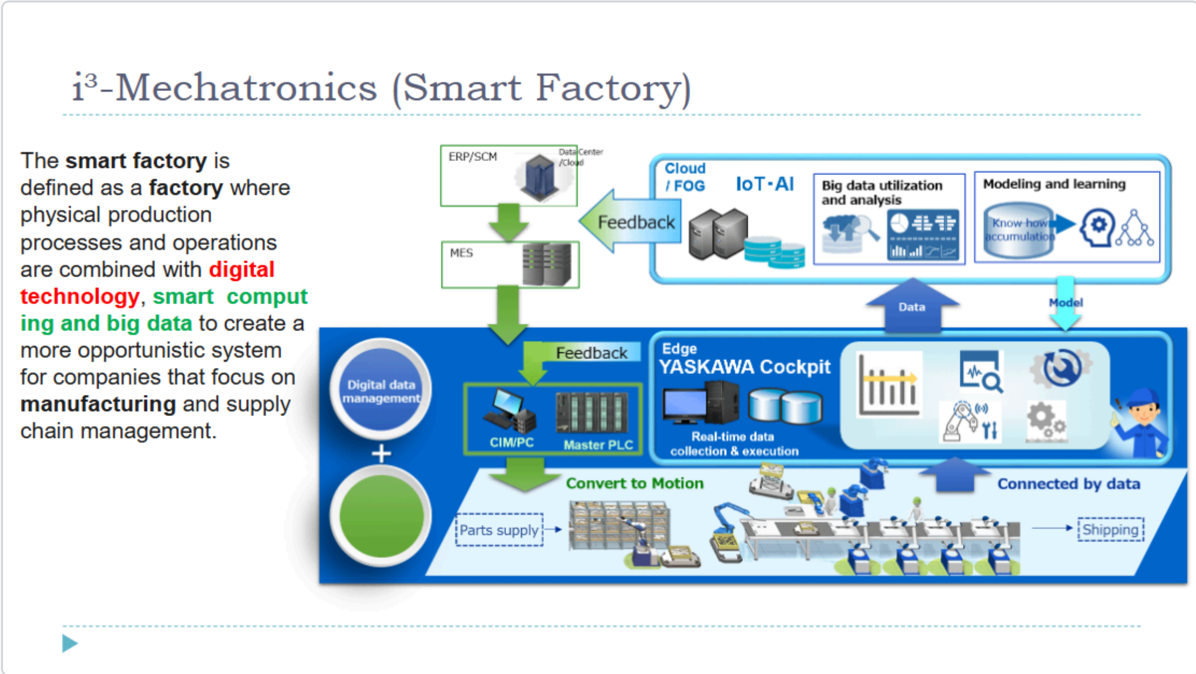


- A robot is a cyber-physical system

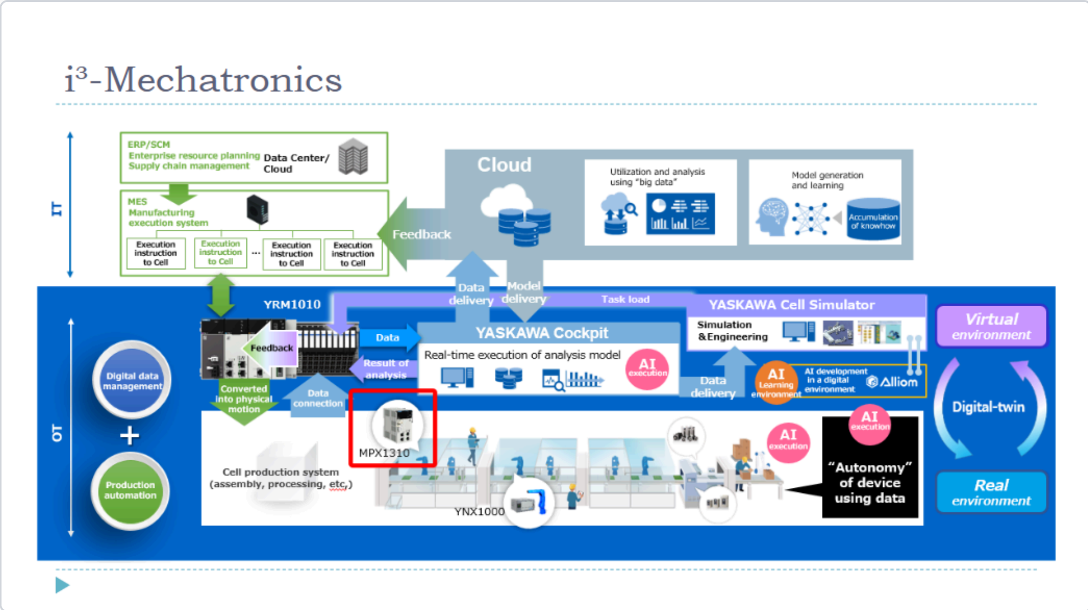
I^3 Mechatronics (Smart Factory)



- YASKAWA, the company who coined the term 'mechatronics', developed i-cubed smart factory solution
- The core of the i-cubed concept is having an integrated solution for collecting and analyzing data and offering new intelligent and innovative insights for improving the level of production and quality
- The smart factory concept starts from ERP, where business and market decisions are

made. These decisions are made based on big data analysis, models, and IoT-AI insights. These decisions are then forwarded to the MES yielding factory-level decisions of what to be produced. The factory-level PCs and PLC controllers receive the order from the MES and feedback from real-time data collection and execution from YASKAWA edge cockpit and based on the models made from big data. They convert these information into action and production in the factory. The process generates data that are further used in the real-time data collection and execution process.

- In essence, smart factory is about using big data and digital technology to make better decisions and creating more opportunities for improvement for manufacturing and supply chain management



- The smart factory concept could be further expanded using **Digital Twin** technology
- A digital twin is a digital model that accurately represents the physical system and is connected to it in real-time. It can gain information about the real system and take action on the real system. This technology could be used for:
    - Predictive maintenance: noticing potential future failure in the physical system and resolving the issue before it occurs
    - Decision making: training a robot in a simulation environment at a much higher

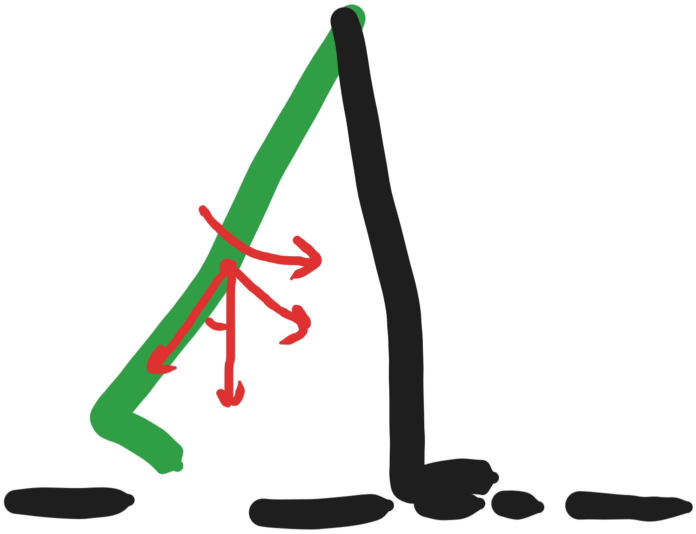
    speed than in reality and using the learned insights in the physical world

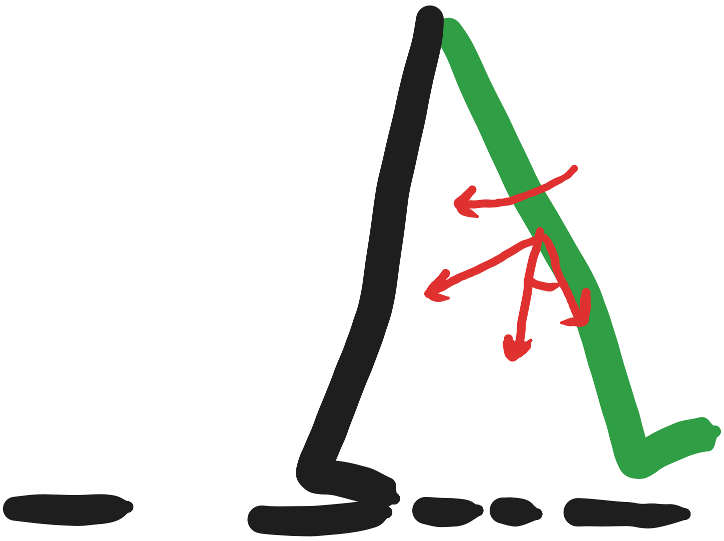
- **Machine learning** consists of:
    - Supervised learning: by showing the machine examples of input and output
    - Unsupervised learning: by showing the machine inputs and letting it notice patterns among these inputs and cluster them into groups
    - Reinforcement learning: by showing the machine what behavior is good and what behavior is bad and letting it learn through trial and error like a child

Microlecture - How to Engineer a Robotic Dog

- Observe the process of going from problem to requirements to conceptual design ...
- Notice that the step of modeling and simulation is skipped just for demonstration
- Notice how optimization occurred

- Limitations of the current system were noted
    - Robot is not agile: it cannot avoid obstacles and cannot be dropped
- The problem got narrowed down (making the robot more agile like the dog) was re-studied for obtaining new requirements
    - The dog muscles stored energy, allowing the dog to make agile maneuvers
    - Muscles elastic behavior provide agility and enables efficient mobility
    - Asimo is the first Humanoid robot, according to the professor. When the energy consumption of the robot was analyzed, it was observed that it consumes more than 10x the amount consumed by humans for walking a distance of 1m. This is because human's walking behavior make use of the inertia of the leg and gravity while walking





- Elasticity? Let's add a spring!
- The spring was also used for measuring and controlling the force on the robot by measuring the displacement of the spring (a much cheaper replacement for force or torque sensors). This lead to the ability of critically damping vibrations

Mechanical Design Considerations for Building Successful Machines

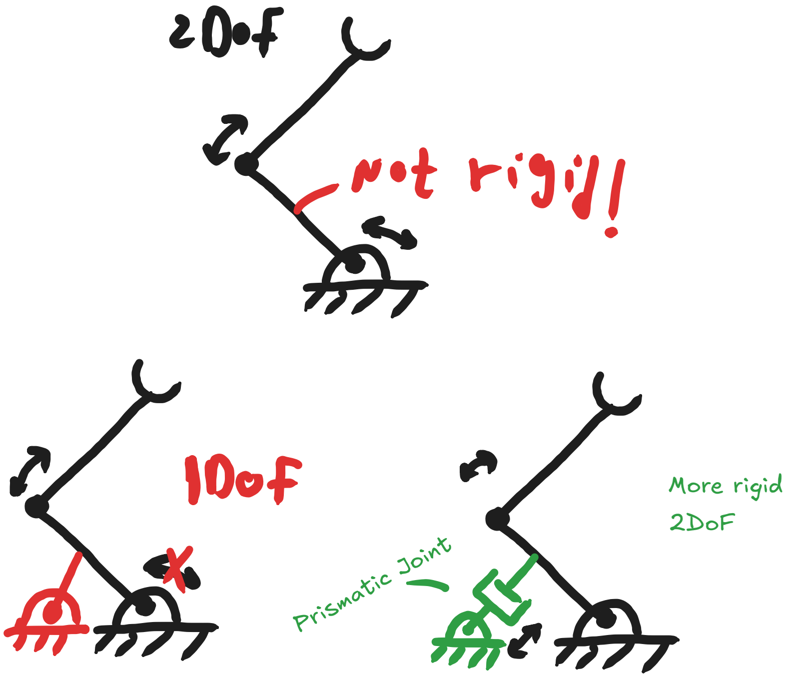
Tips for Building Successful Machines through Proper Structure Connections and Interfaces

- Any machine usually has many limitations for example limitations of: **weight**, **size**, **energy**, etc. So, you have to design and develop a very light, strong, very low friction machine, etc.
- There are **five key elements** for efficient machine design:
  1. shaft bearings and supports,
  2. material and its cross section geometry,
  3. machine rigidity,
  4. degrees of freedoms and mobility,
  5. power, and correct actuator sizing configurations.

- The lighter, the easier it is to control and the faster the system responds: $\omega_n = \sqrt{\frac{K}{M}}$; remember $t_{\text{settling}} = \frac{4}{\zeta\omega_n}$
- The less friction, the less non-linearity, the better you can estimate the systems parameters and control
- It should not just achieve the function, it should achieve the function efficiently: the

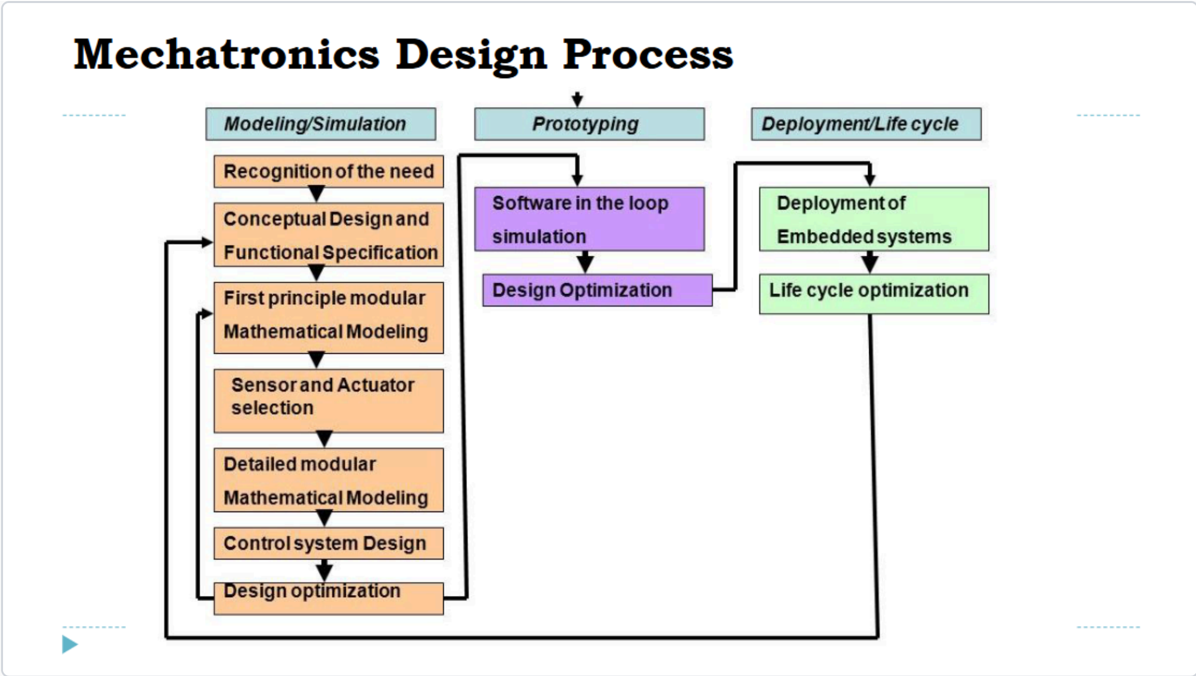
lighter the better

- The more rigid, the easier it is to control
- Watch out of reducing the number of desired degrees of freedom while trying to make your system more rigid



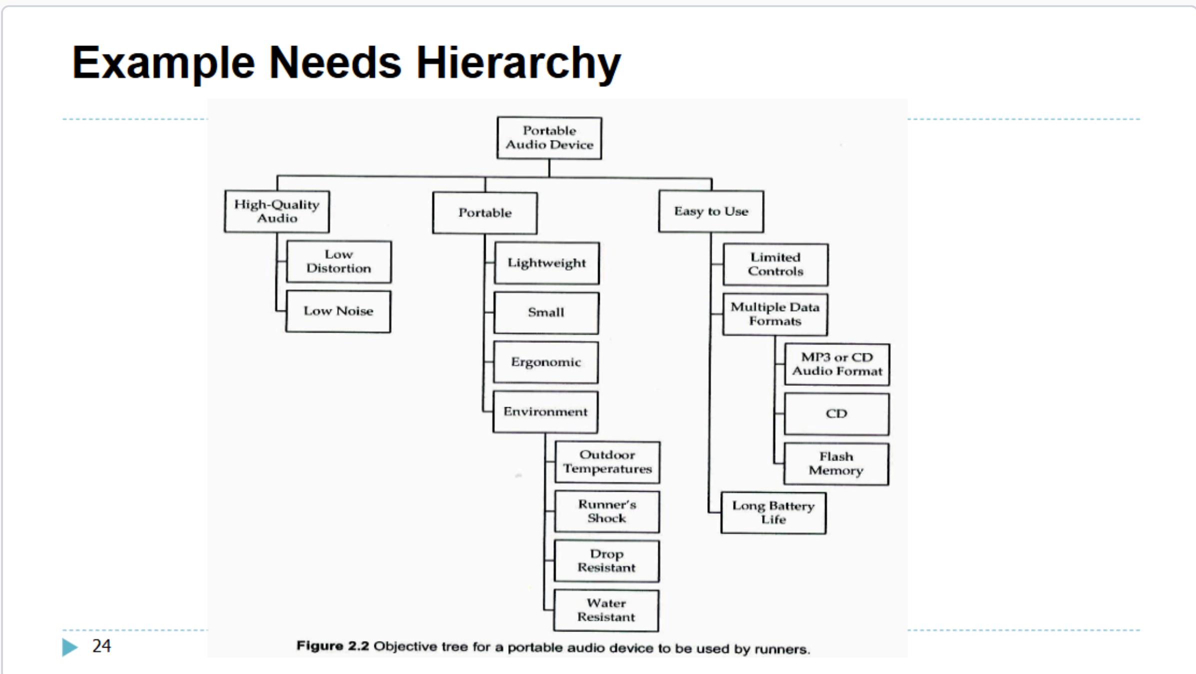
- Over-sizing the actuator means higher cost and weight
    - A trick is using [counter-weight or constant-force springs] (this is known as [Gravity Compensation])

Follow Mechatronic Systems Design Process



- Modeling and simulation are crucial for reducing development time and cost

Product Design = Problem/Need → Engineering Requirements



- Researching the market and understanding customer needs
- Breaking down the problem or desire into conceptual (qualitative) detailed needs
- There is a distinction between marketing requirements and engineering requirements. Marketing requirements vaguely describe customer needs, while engineering requirements are quantitative and detailed
- Product requirements in general are usually handled by product design teams

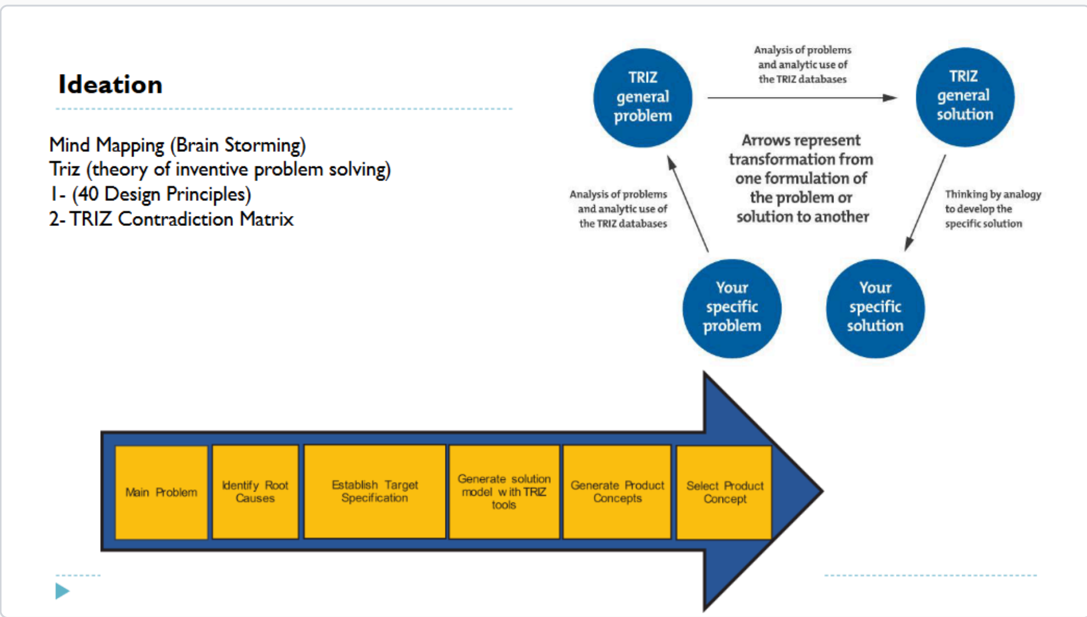
Functional Structure Diagram = Requirements → Conceptual Design (Functional Block Diagram)

- This is a tool that can be used for going from the needs and requirements to a conceptual design (layout/block diagram) of the system

> **Note**: in the context of mechatronic systems design, functional block diagrams are mechatronic block diagrams

How to Innovate and Solve Problems

- Throughout the mechatronic systems design process, problems requiring creative solutions will pop up
- TRIZ is a collection of general solutions to general common problems that can be applied to your specific problem



- TRIZ compiles:
    - General problems/features to improve (https://www.innovation-triz.com/TRIZ40/TRIZ_Matrix.xls)
    - Check out TRIZ40 - : Solve Technical Problems with TRIZ Methodology
    - General solutions