2ECDE11 – Cyber Physical System

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Syllabus

UNIT I: Introduction to Cyber-Physical Systems	**05**
Cyber-Physical Systems (CPS) in the real world, Basic principles of design and validation of CPS, Industry 4.0, AutoSAR, IIOT implications, Building Automation, Medical CPS	
UNIT II: CPS - Platform Components	**06**
CPS HW platforms - Processors, Sensors, Actuators, CPS Network – Wireless Hart, CAN, Automotive Ethernet, CPS Software stack - RTOS, Scheduling Real-Time control tasks	
UNIT III: Principles of Automated Control Design	**08**
Basic control theory, Dynamical Systems, and Stability, Controller Design Techniques, Stability Analysis: CFLs, MLFs, stability under slow switching, Performance under Packet drop and Noise, Tutorial: MATLAB toolboxes - Simulink, State flow	
UNIT IV: CPS Implementation	**07**
Features, software components, Mapping software components to ECUs, CPS Performance Analysis - effect of scheduling, bus latency, sense and actuation faults on control performance, network congestion, Control, Bus and Network Scheduling using True-time	

Syllabus

UNIT V: Formal Methods for Safety Assurance of Cyber-Physical Systems **07**

Advanced automata-based modeling and analysis, Basic introduction and examples, Timed and Hybrid Automata Formal Analysis, Flow pipe construction, reachability analysis, Analysis of CPS Software, Weakest Pre-conditions, Hybrid Automata Modeling

UNIT VI: Secure Deployment of CPS **06**

Attack models, Secure Task mapping and Partitioning, State estimation for attack detection, Case study - Vehicle ABS hacking, Power Distribution, and Attacks on Smart Grids

UNIT VII: CPS Case Studies and Tutorials **06**

Automotive: SW controllers for ABS, ACC, Lane Departure Warning, Suspension Control, Healthcare: Artificial Pancreas/Infusion Pump/Pacemaker, Green Buildings: automated lighting, AC control, and Agriculture

Self-Study:

The self-study contents will be declared at the commencement of the semester. Around 10% of the questions will be asked from self-study contents.

Course Structure

L	T	P	C
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Course Outcomes (COs):

At the end of the course, the students will be able to -

1. address challenges in implementing a cyber-physical system from a computational perspective.
2. integrate real-valued and dense time real-time systems with software-based discrete automated control.
3. design of cyber-physical systems using formal methods.
4. validate cyber-physical system problems for safety assurance and security aspects.

Suggested Readings:

1. E.A.Lee, Sanjit Seshia, Introduction to Embedded Systems: A Cyber-Physical Systems Approach, MIT Press
2. Rajeev Alur, Principles of Cyber-Physical Systems, MIT Press

Course Assessment Policy

Continuous Evaluation (60%)	
Class Test (CT) [Weightage - **35%**]	**Semester End Examination (SEE)** Weightage-**40%**
Special Assignment (SA) [Marks-**30**,Weightage - **30%**]	
Sessional Exam (SE) [Weightage - **35%,**]	

Introduction: Cyber Physical Systems

- A cyber-physical system (CPS) is an integration of computation with physical processes whose behavior is defined by both cyber and physical parts of the system.

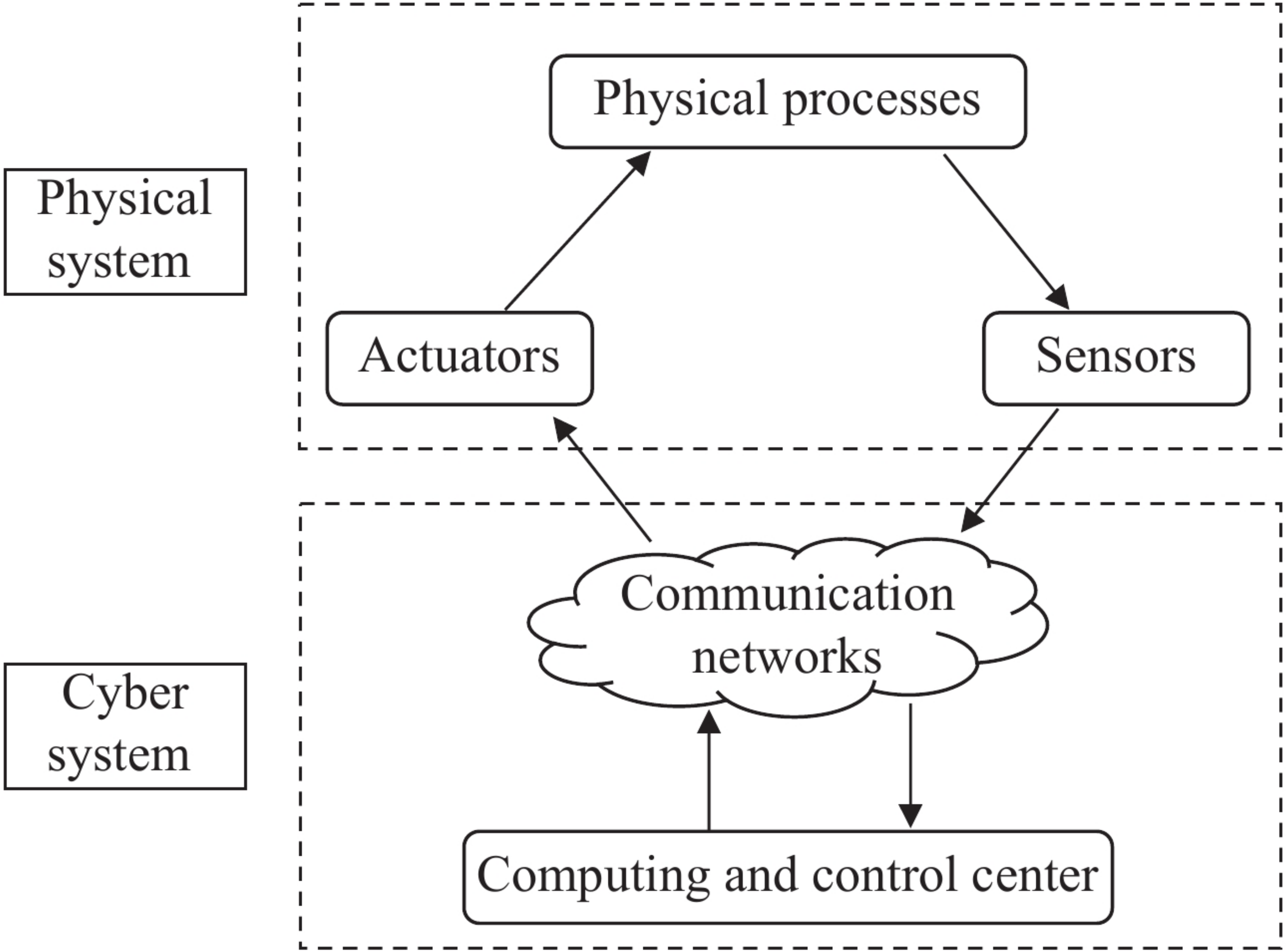
- It enables advanced functionalities through the integration of real-time computing and physical operations.

- The term "cyber" is a prefix derived from the word "cybernetics," which refers to the science of communication and automatic control systems in both machines and living things.

Introduction

- Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa.

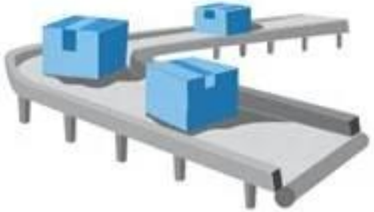
- As an intellectual challenge, CPS is about the intersection, not the union, of the physical and the cyber. It is not sufficient to separately understand the physical components and the computational components. We must instead understand their interaction.


Physical system
Cyber system
Physical processes
Actuators
Sensors
Communication networks
Computing and control center

Think-Pair-Share
(Components, Benefits, Applications)

- Industry 4.0
- AutoSAR
- Industrial IoT

Industry 4.0

END OF THE 18TH CENTURY	START OF THE 20TH CENTURY	START OF THE 1970S	PRESENT
			
INDUSTRY 1.0 **Mechanization**	**INDUSTRY 2.0** **Electrification**	**INDUSTRY 3.0** **Automatization**	**INDUSTRY 4.0** **Cyber-Physical Systems**
Introduced mechanization of production by using water and steam to increase production capacity and productivity, versus manual craft work	Introduced labor-based mass production (assembly lines) powered by electrical energy	Introduced electronics and computers to replace manual work by stand-alone robotic systems	The convergence of physical, digital, and virtual environments through **Cyber-Physical Systems (CPS)** and the **Internet of Things (IoT)**
1784 First mechanical loom	**1870** First production line, Cincinnati slaughterhouses	**1969** First programmable logic controller (PLC), Modicon 084	

Key Components of Industry 4.0

- Internet of Things
- Cyber Physical Systems
- Big Data Analytics
- Cloud Computing
- AI and ML
- Autonomous Robots
- Additive Manufacturing (3D Printing)
- Augmented Reality and Virtual Reality
- Smart Factories

Key Benefits of Industry 4.0

- Increased efficiency
- Enhanced Flexibility
- Improved quality
- Cost optimization
- Innovation

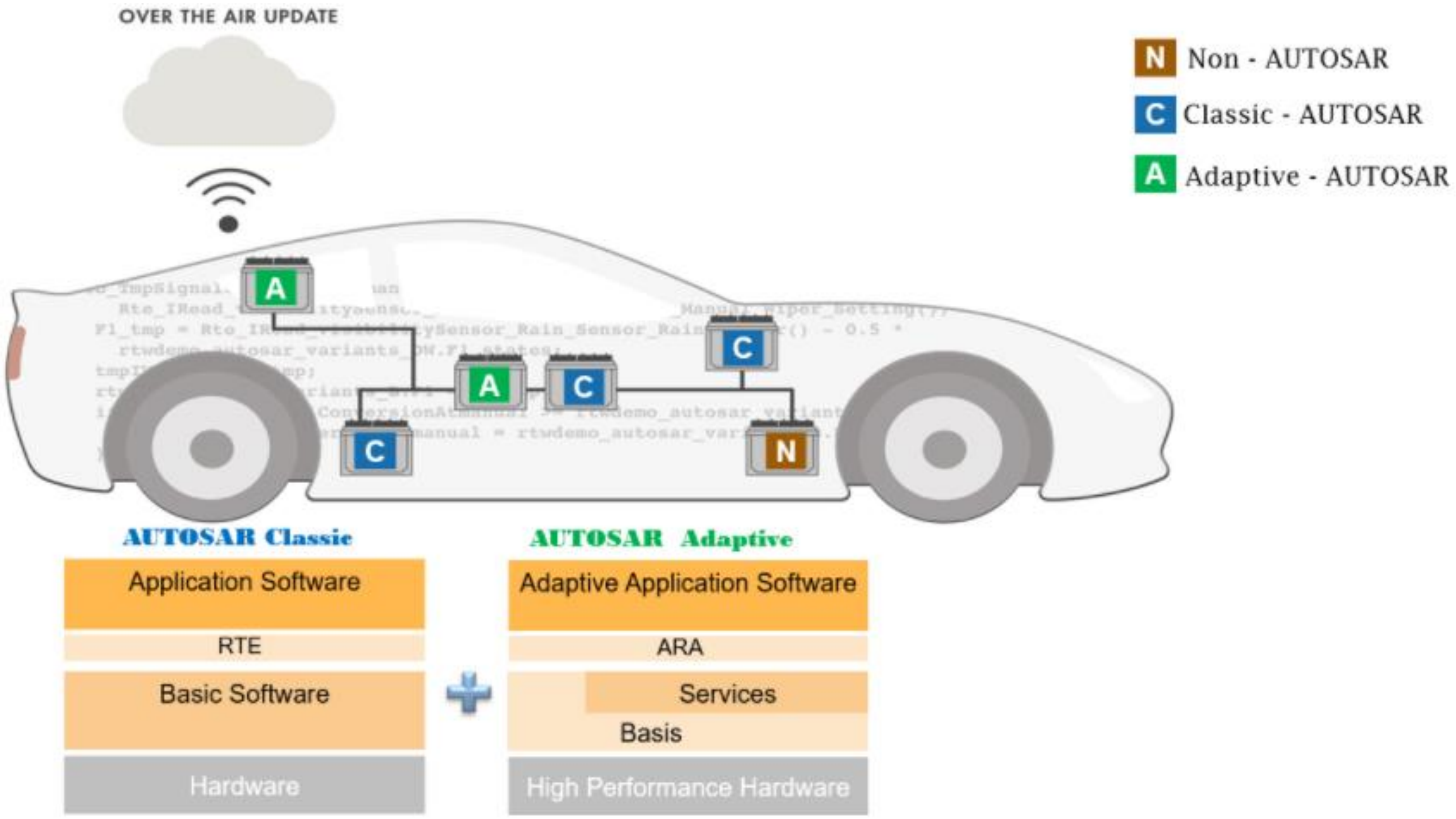
Key Applications of Industry 4.0

- Automotive
- Healthcare
- Consumer goods
- Energy
- Construction

Challenges of Industry 4.0

- Cybersecurity
- Interoperability
- Skill Development
- Investment
- Regulations and Standards

AutoSAR Automotive Open System Architecture



Main Goals of AutoSAR

- Standardization: Interoperability and reusability of software
- Scalability: Different platform and vehicle but unique software
- Flexibility: Different hardware and software for different units
- Modularity: Small modular structure of components
- Safety and Security: Robust framework that meet industry standard
- Maintainability: Ease of upgrading software

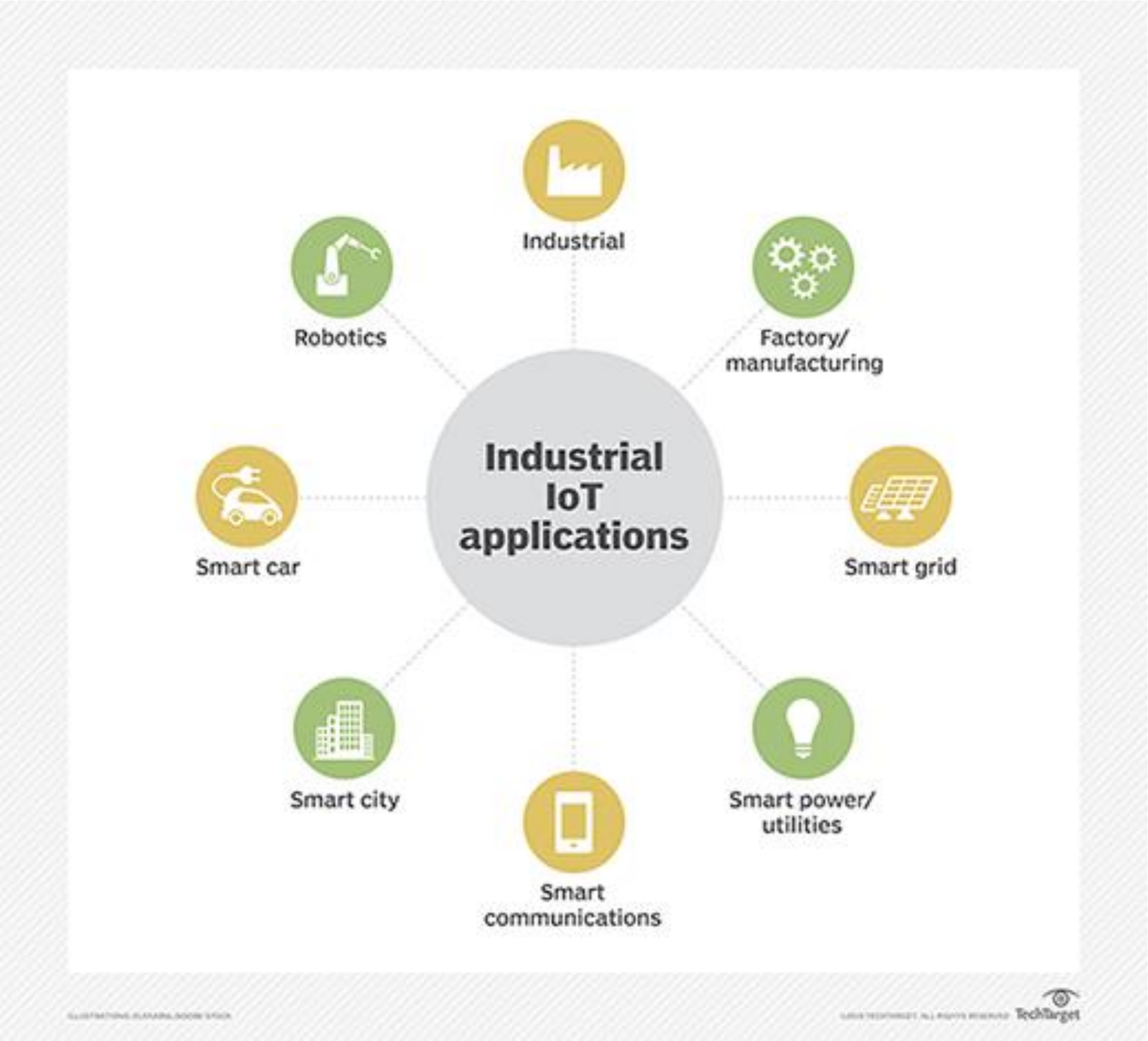
Components of AutoSAR

- Basic Software and Hardware: Basic circuits, Communication, Software management, Memory Management
- Runtime Environment: Communication between Software components and basic software
- Application software: Execute specific tasks
- Methodology: Developing, configuring and integrating software components

Benefits of AutoSAR

- Reduced development costs
- Increased quality
- Vendor Independence
- Future Proofing
- AUTOSAR is used in various automotive applications such as engine control, transmission control, vehicle dynamics, driver assistance systems, and infotainment systems, among others. It has become a crucial framework for modern automotive software development, driving innovation and efficiency in the automotive industry.

IIoT Applications



Components of IIoT

- Sensors and Actuators
- Communication/Connectivity
- Edge Computing
- Cloud Computing
- Big data analytics
- Cyber security
- AI and ML

Benefits of IIoT

- Improved efficiency
- Predictive Maintenance
- Enhanced safety
- Improved Product quality
- Optimised supply chain management
- Energy Management

Applications of IIoT

- Manufacturing
- Energy management
- Transportation
- Healthcare
- Agriculture

IoT and CPS

Differences between Internet of Things (IoT) and Cyber Physical Systems (CPS)

Focus and Scope		
IoT		CPS
To connect devices to the internet to collect and exchange data, enhancing functionality and providing insights	Objective	To create systems where computational elements monitor and control physical processes, often with real-time feedback loops
Primarily on connectivity and communication between devices	Focus	Integration and coordination between computational processes and physical processes
Encompasses a wide range of devices and applications, from consumer electronics to industrial machines.	Scope	More specific to systems where physical processes are tightly integrated with computational control.

Components and Architecture

Components and Architecture		
IoT		CPS
Sensors, actuators, communication networks, cloud computing, and data analytics platforms.	Component	Sensors, actuators, embedded systems, real-time control systems, and communication networks.
Often follows a cloud-centric model where data is collected from devices and processed in the cloud.	Architecture	Often includes a more distributed and real-time control architecture where computational elements directly interact with physical processes
Mainly focuses on data collection and sharing over the internet	Communication	Emphasizes real-time feedback and control, often requiring low latency and high reliability.

Applications		
IoT		CPS
Consumer Applications: Smart homes, wearable devices, and connected appliances.		Critical Infrastructure: Smart grids, water distribution systems, and transportation networks.
Industrial Applications: Smart manufacturing, asset tracking, and predictive maintenance.		Autonomous Systems: Self-driving cars, unmanned aerial vehicles, and robotic systems.
Urban Applications: Smart cities, intelligent transportation systems, and environmental monitoring.		Medical Systems: Telemedicine, health monitoring, and robotic surgery.

Data and Control		
IoT		CPS
Collects and transmits large amounts of data to be analyzed, often in the cloud.	Data Handling	Emphasizes real-time data processing and decision-making at the edge or within the system.
Generally involves monitoring and managing devices remotely through dashboards and apps.	Control	Requires precise and often real-time control over physical processes, integrating computational intelligence directly with physical operations.

Design Considerations		
IoT		CPS
Scalability: Designed to handle a large number of devices and vast amounts of data.		Reliability: Must ensure high reliability and robustness, especially in safety-critical applications.
Interoperability: Focuses on ensuring different devices and platforms can communicate and work together.		Real-Time Performance: Requires strict real-time performance and low-latency communication for effective control.

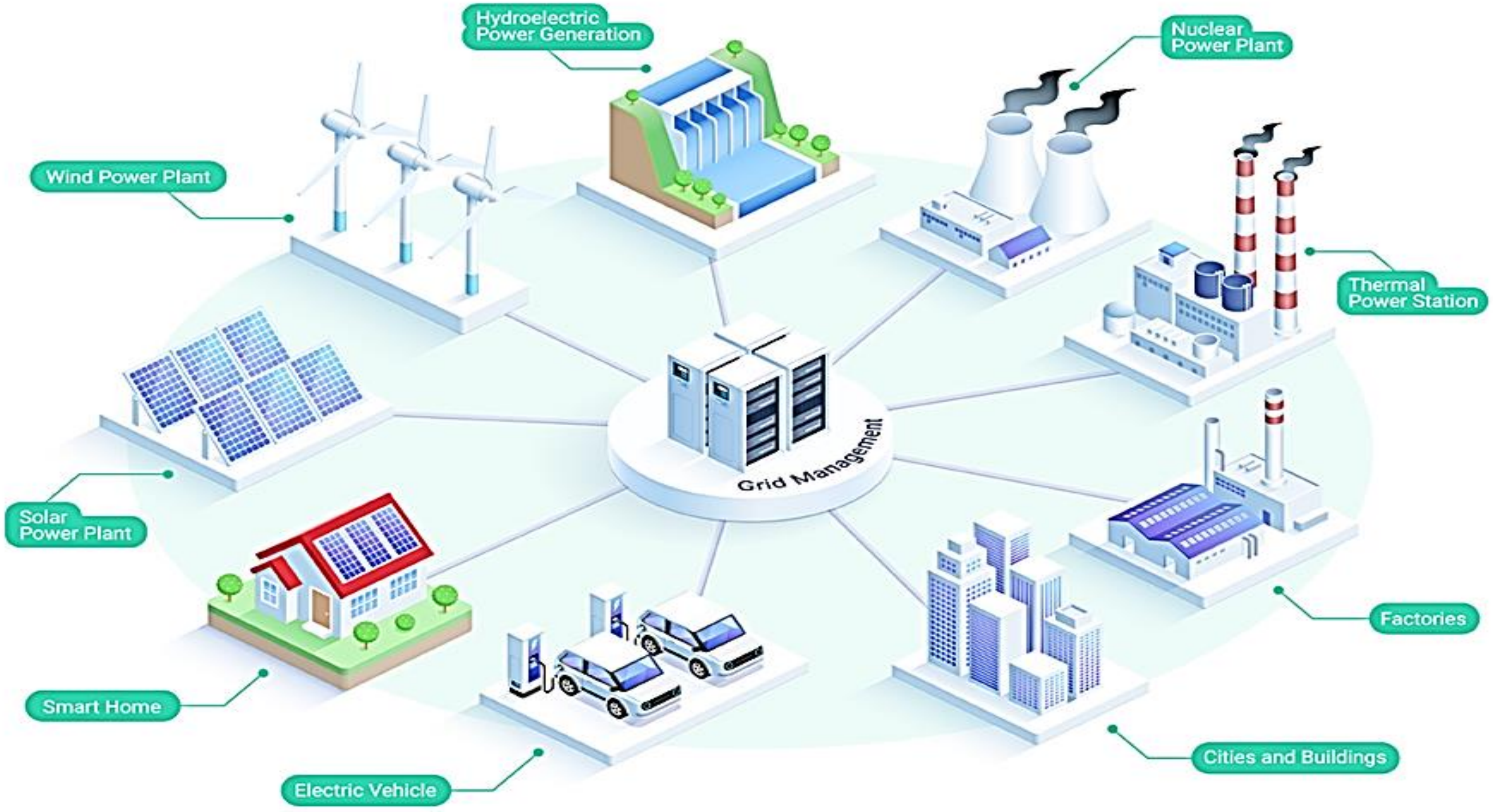
Summary

- IoT is about connecting devices to the internet to gather and exchange data, enhancing device functionality and providing insights.

- CPS is about the tight integration of computational and physical processes, focusing on real-time monitoring and control to create systems that respond dynamically to changes in their environment.

Application Domains of CPS

Smart Grid


Hydroelectric Power Generation
Nuclear Power Plant
Wind Power Plant
Thermal Power Station
Grid Management
Solar Power Plant
Factories
Smart Home
Cities and Buildings
Electric Vehicle

Smart Grids

- Description: Smart grids use CPS to enhance the efficiency, reliability, and sustainability of electricity production and distribution.
- Components: Sensors, smart meters, distributed energy resources, and control systems.
- Benefits: Improved energy distribution, better integration of renewable energy sources, real-time monitoring and response to energy demands, and enhanced fault detection and self-healing capabilities.

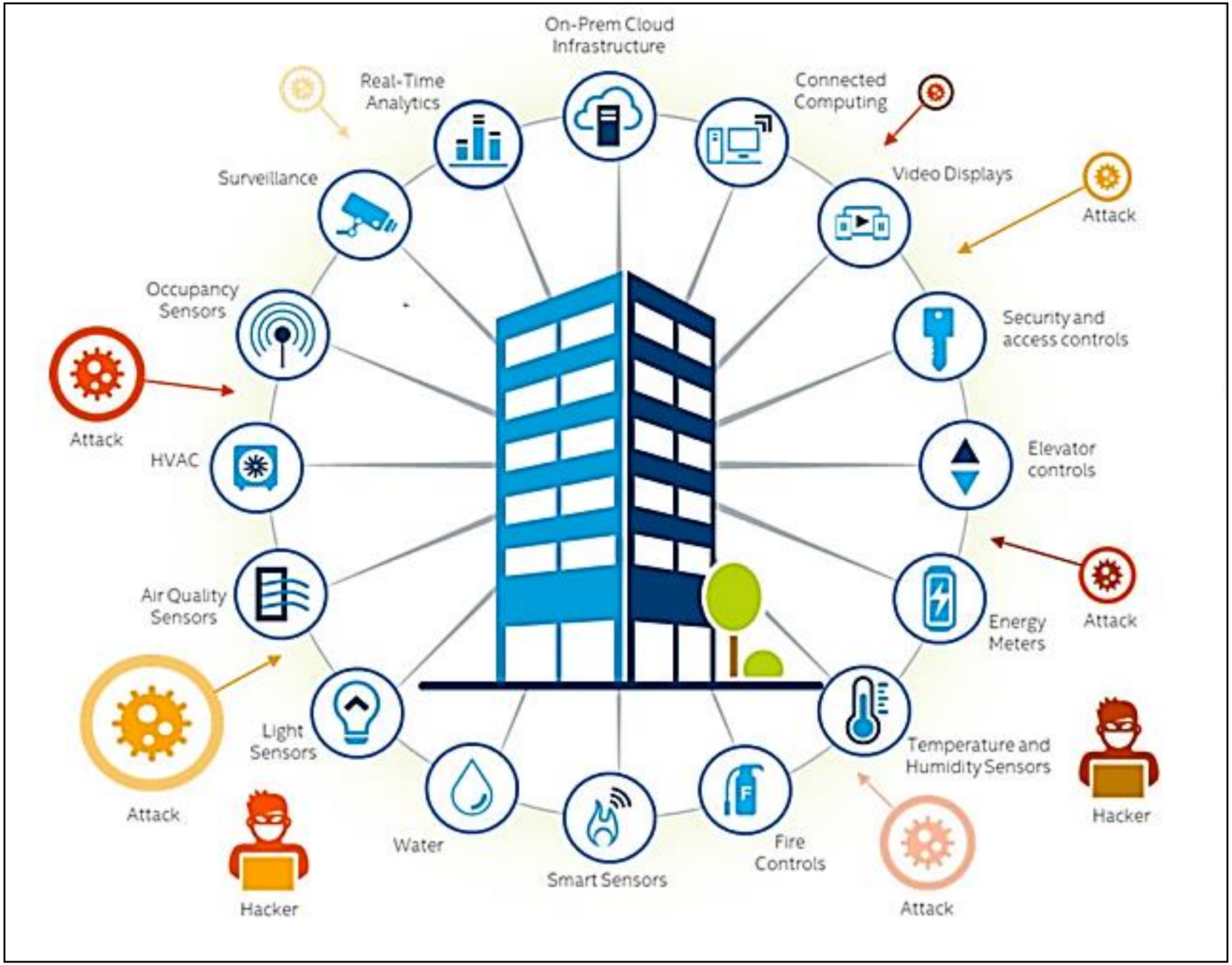
Industrial Automation

Description: Factories use CPS for automation and optimization of manufacturing processes.

Components: Robotics, sensors, machine learning algorithms, and networked control systems.

Benefits: Higher productivity, reduced downtime, and greater flexibility in production processes.

Smart Buildings



Smart Buildings

- Description: Buildings equipped with CPS to optimize energy use, security, and comfort.
- Components: HVAC systems, lighting controls, security systems, and occupancy sensors.
- Benefits: Energy savings, improved comfort, and enhanced security.

Smart Healthcare Systems

Description: CPS in healthcare includes systems that monitor and manage patient health in real-time.

Components: Wearable devices, implantable sensors, and telemedicine platforms.

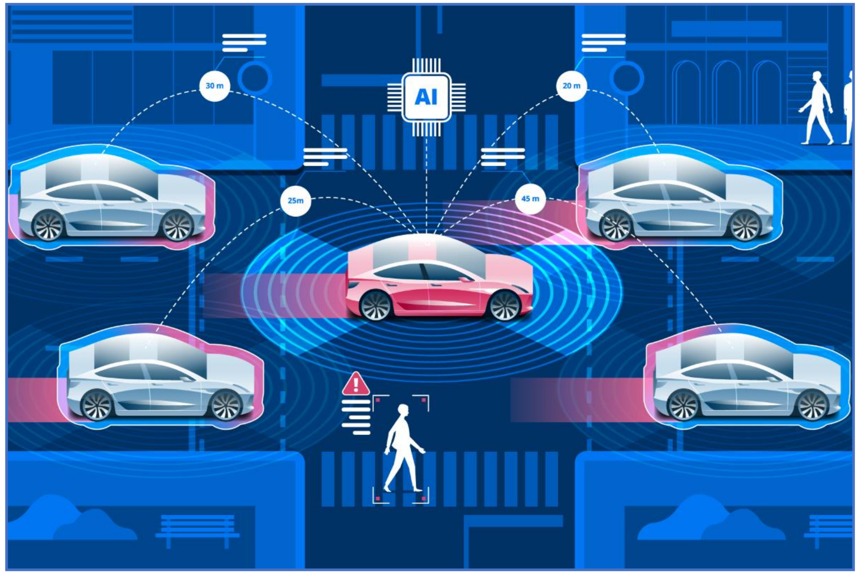
Benefits: Continuous health monitoring, early detection of health issues, and personalized treatment plans.

Smart Transportation Systems

Autonomous Vehicles

- Description: Autonomous vehicles use CPS to navigate and operate without human intervention.
- Components: Lidar, radar, cameras, GPS, and advanced algorithms for perception, planning, and control.
- Benefits: Increased safety, reduced traffic congestion, and improved fuel efficiency.

Autonomous Vehicles



- Consider a city where traffic lights and cars cooperate to ensure efficient flow of traffic.
- In particular, imagine never having to stop at a red light unless there is actual cross traffic.
- Such a system could be realized with expensive infrastructure that detects cars on the road. But a better approach might be to have the cars themselves cooperate.
- They track their position and communicate to cooperatively use shared resources such as intersections.
- Making such a system reliable, of course, is essential to its viability. Failures could be disastrous.

Smart Transportation Systems

- Description: CPS are used to manage and optimize transportation infrastructure.
- Components: Traffic signals, road sensors, and vehicle-to-infrastructure communication systems.
- Benefits: Reduced traffic congestion, improved safety, and enhanced mobility.

Smart Agriculture

Description: Precision agriculture uses CPS to optimize farming practices.

Components: Drones, soil sensors, weather stations, and automated irrigation systems.

Benefits: Increased crop yields, efficient use of resources, and reduced environmental impact.

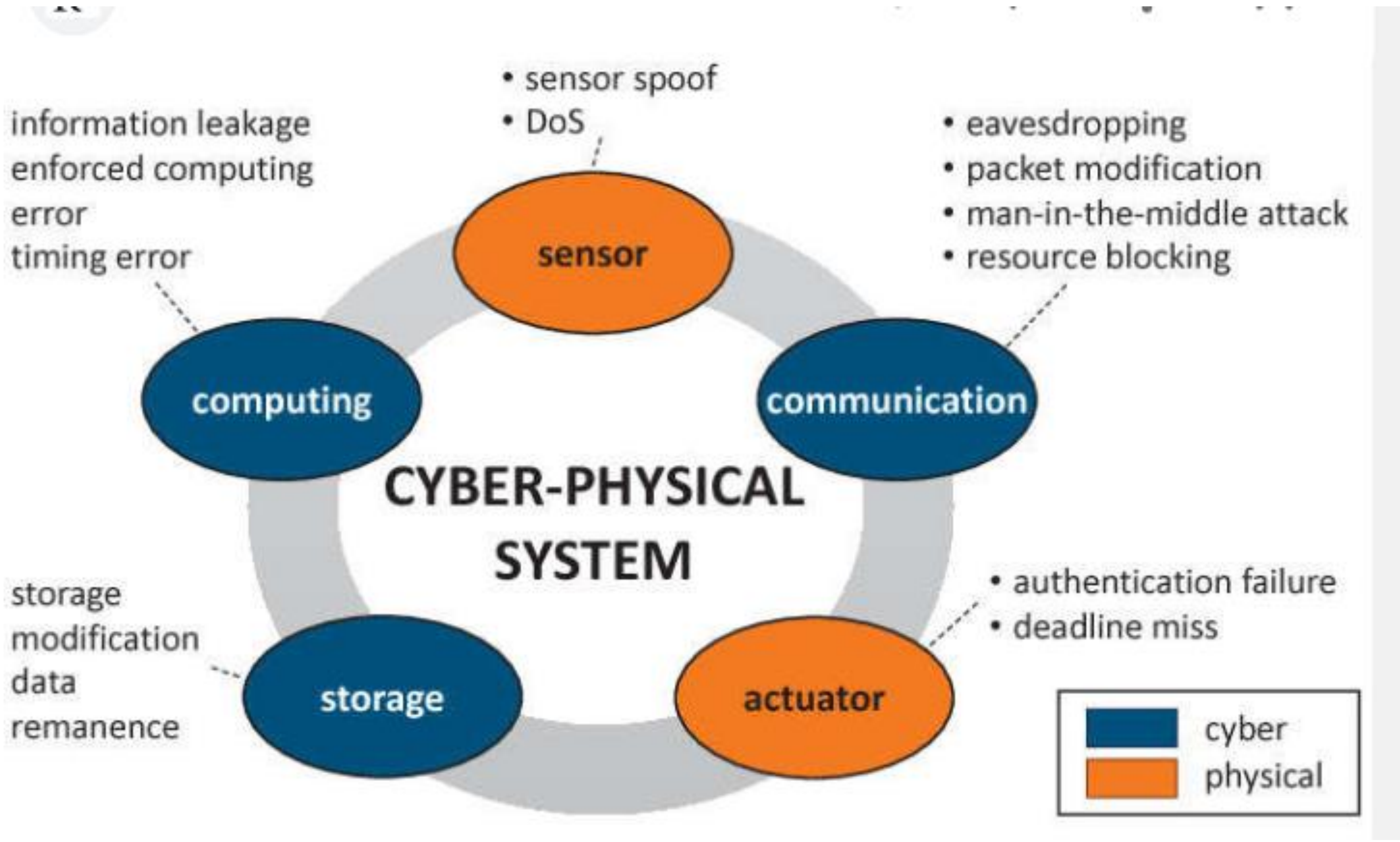
Environmental Monitoring

Description: CPS are used to monitor and manage environmental conditions.

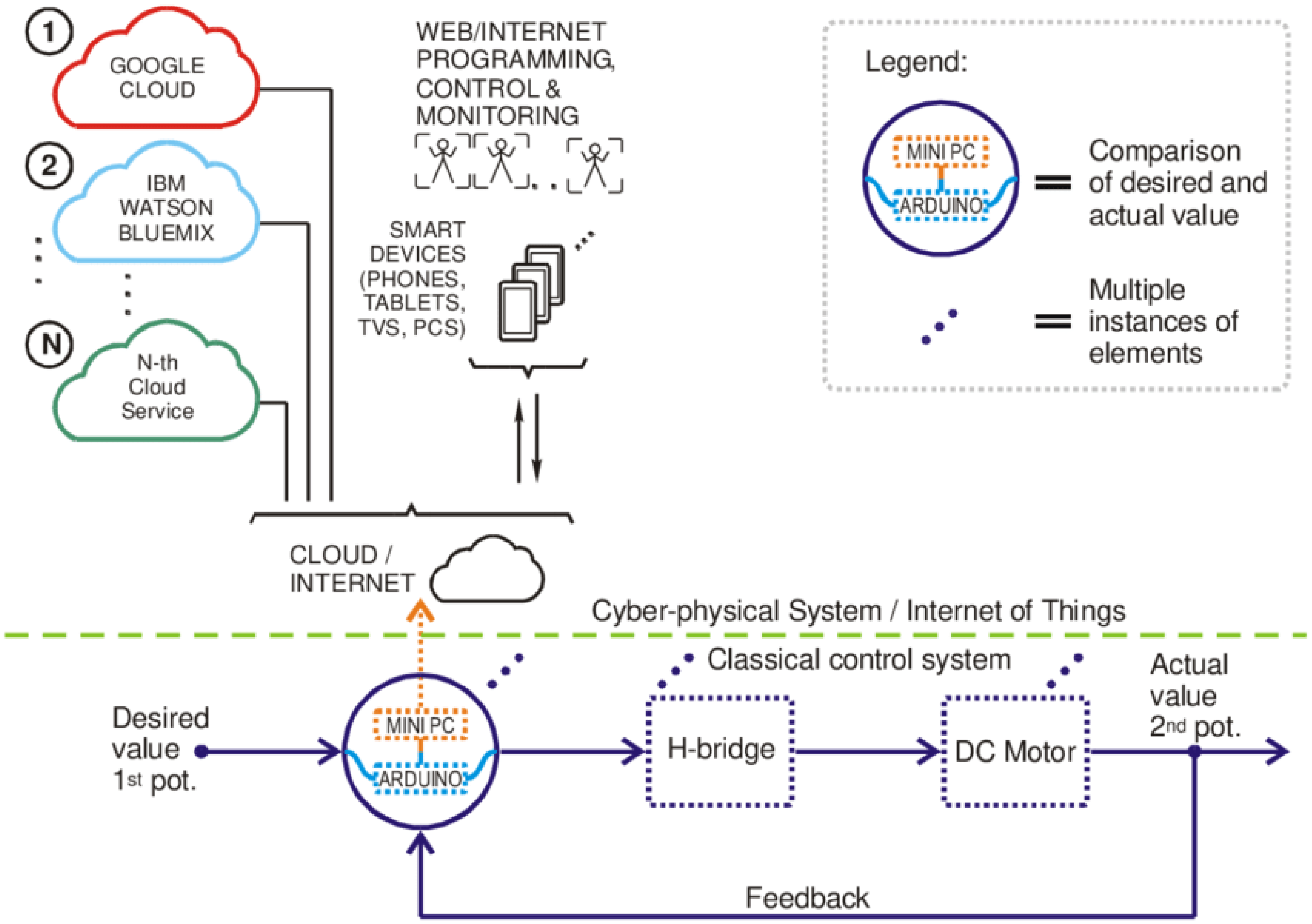
Components: Sensor networks, data analytics platforms, and automated response systems.

Benefits: Early detection of natural disasters, better management of natural resources, and improved environmental protection.

CPS Platform Components



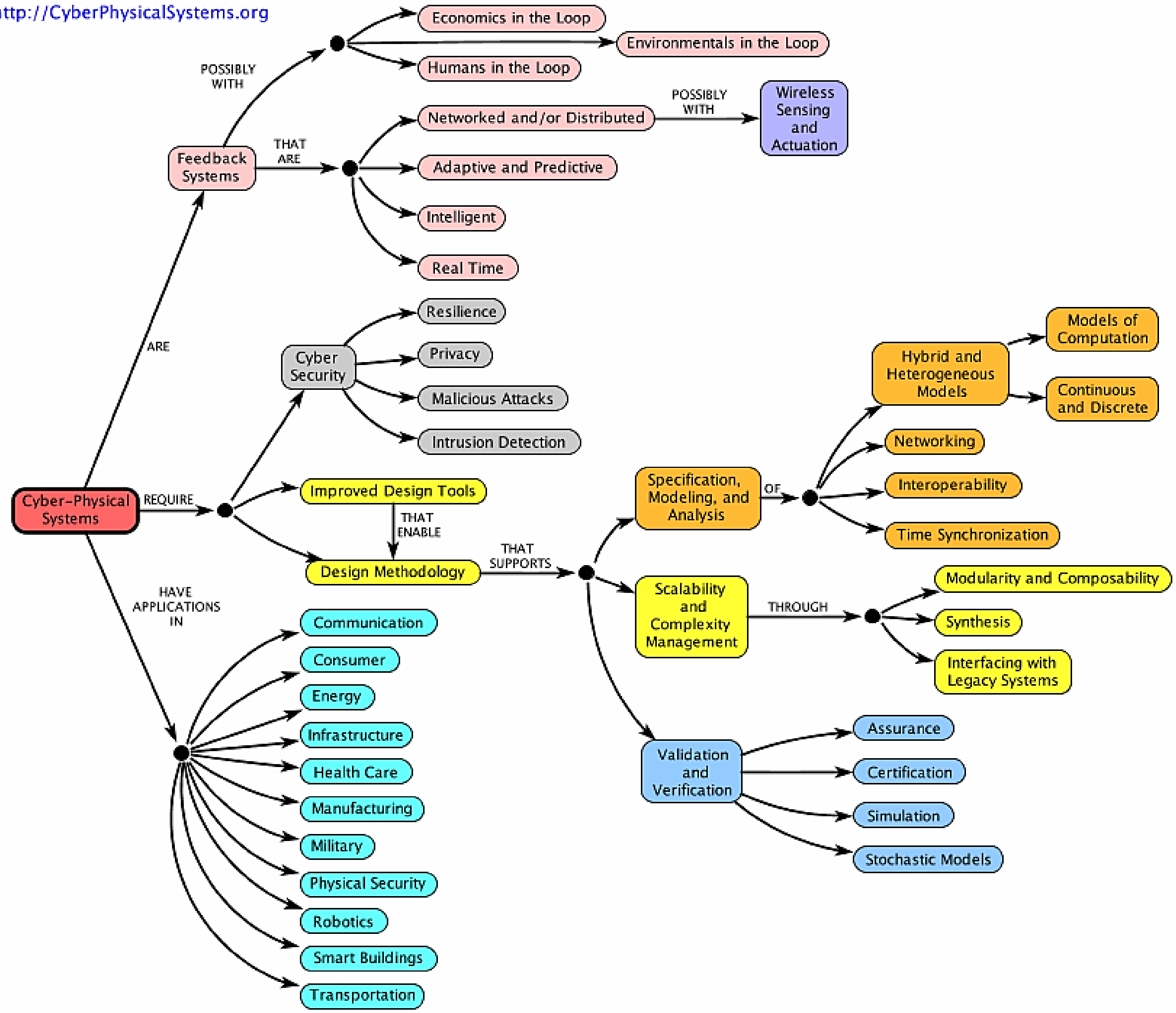
CPS Control Design



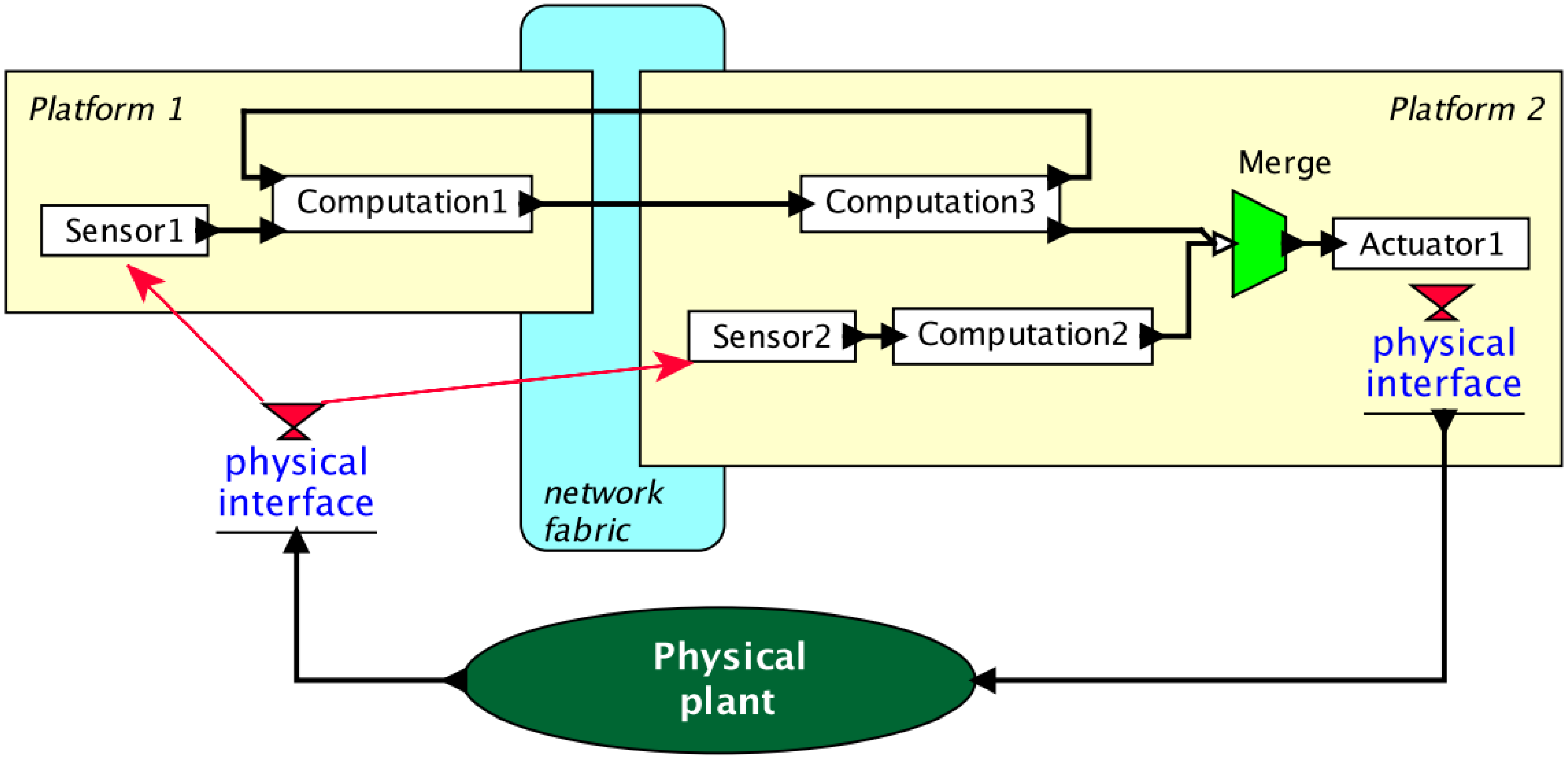
Cyber-Physical Systems – a Concept Map

See authors and contributors.

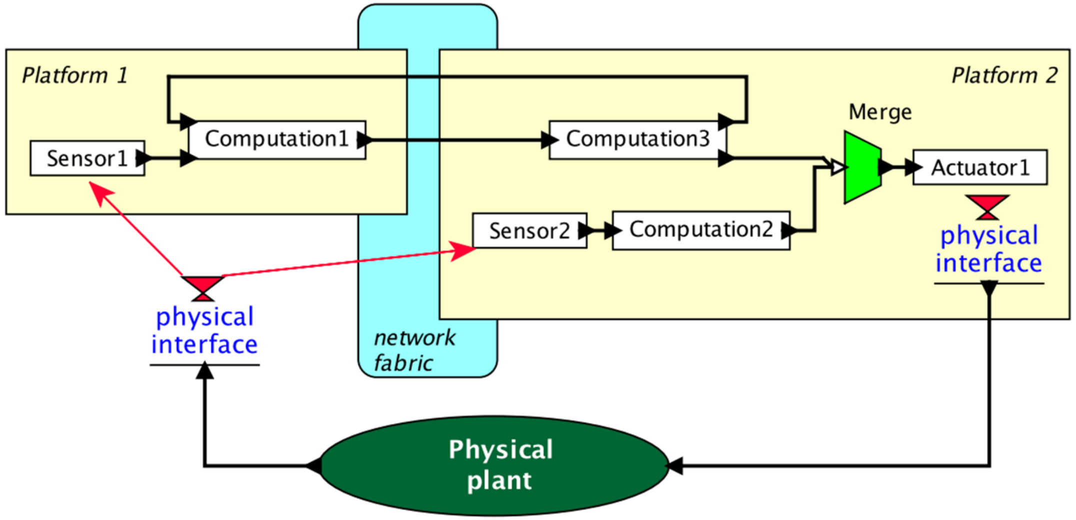
http://CyberPhysicalSystems.org



Basic Block diagram

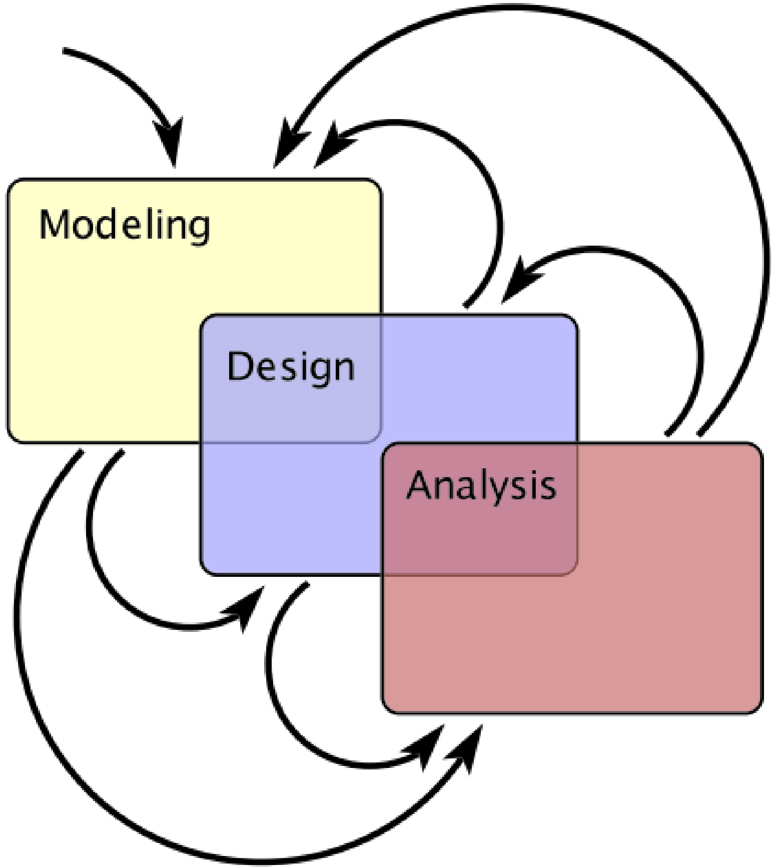


Basic Block diagram of CPS



- First, the **physical plant** is the “physical” part of a cyber-physical system. It is simply that part of the system that is not realized with computers or digital networks.
- It can include mechanical parts, biological or chemical processes, or human operators.
- Second, there are one or more computational **platforms**, which consist of sensors, actuators, one or more computers, and (possibly) one or more operating systems.
- Third, there is a **network fabric**, which provides the mechanisms for the computers to communicate.
- Together, the platforms and the network fabric form the “cyber” part of the cyber-physical system.

Iterative Process



- Modeling: What system does
- Design: How system works
- Analysis: Why system does

Quadrotor

The STARMAC quadrotor aircraft in flight (reproduced with permission)

- Weight
- Balancing Thrust and torque of motors
- Localization
- Vehicle dynamics
- Landing

Conclusion

- Cyber-physical systems are heterogeneous blends by nature. They combine computation, communication, and physical dynamics.
- They are harder to model, harder to design, and harder to analyze than homogeneous systems.

Thank You…