Systems Engineering, Data Analytics, and Systems Thinking: Moving Ahead to New and More Complex Challenges

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Introduction

In our companion paper, we review and present the challenges and opportunities for the systems engineering discipline and community in the *Fourth Industrial Revolution*.

We present an integrated view of systems engineering, system thinking, and data analytics.

About Systems Engineering (historically)

- Systems Engineering has developed a rich foundation of standard models, methods, and processes
- Assumptions have been that the system has a:
  - Stable set of requirements
  - Manageable set of stakeholders
  - Well-defined set of boundaries for the system

About Systems Engineering (circa 2018)

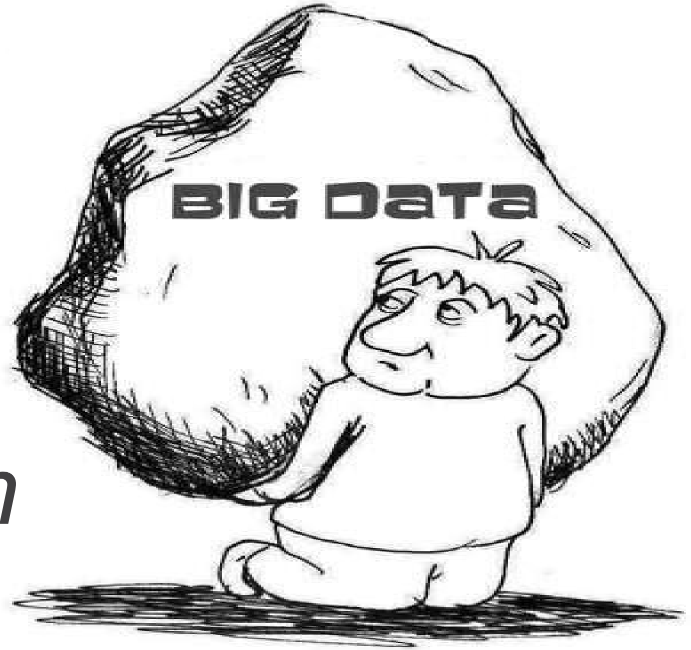
- Over the years…
  - The number (and clarity, stability) of requirements has grown
  - The number of stakeholders has grown
  - Boundaries have become larger and less clear

What's Changed?

- Big data
- Internet of Things

- Massive Digitization
- Cloud Computing
- Artificial Intelligence
- Augmented Reality
- …

- Big Data
  - Annual global internet traffic is forecast to reach *3.3 zettabytes* by 2021
  - 3,300,000,000,000,000,000,000
  - *That's 40 terabytes per person in the world per year!*

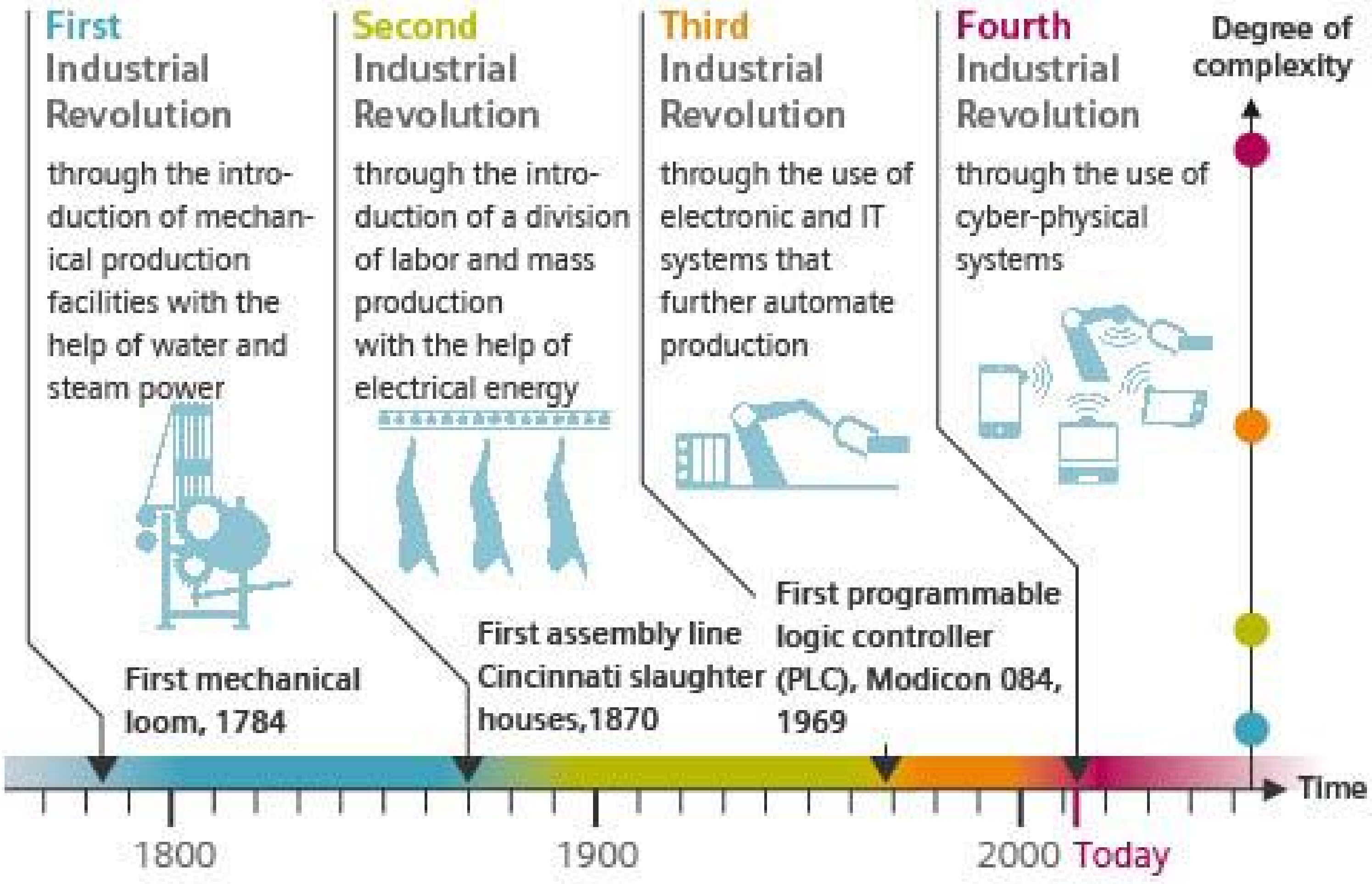


- The Internet of Things
  - Challenges our notions of system constraints and borders

In the Future…

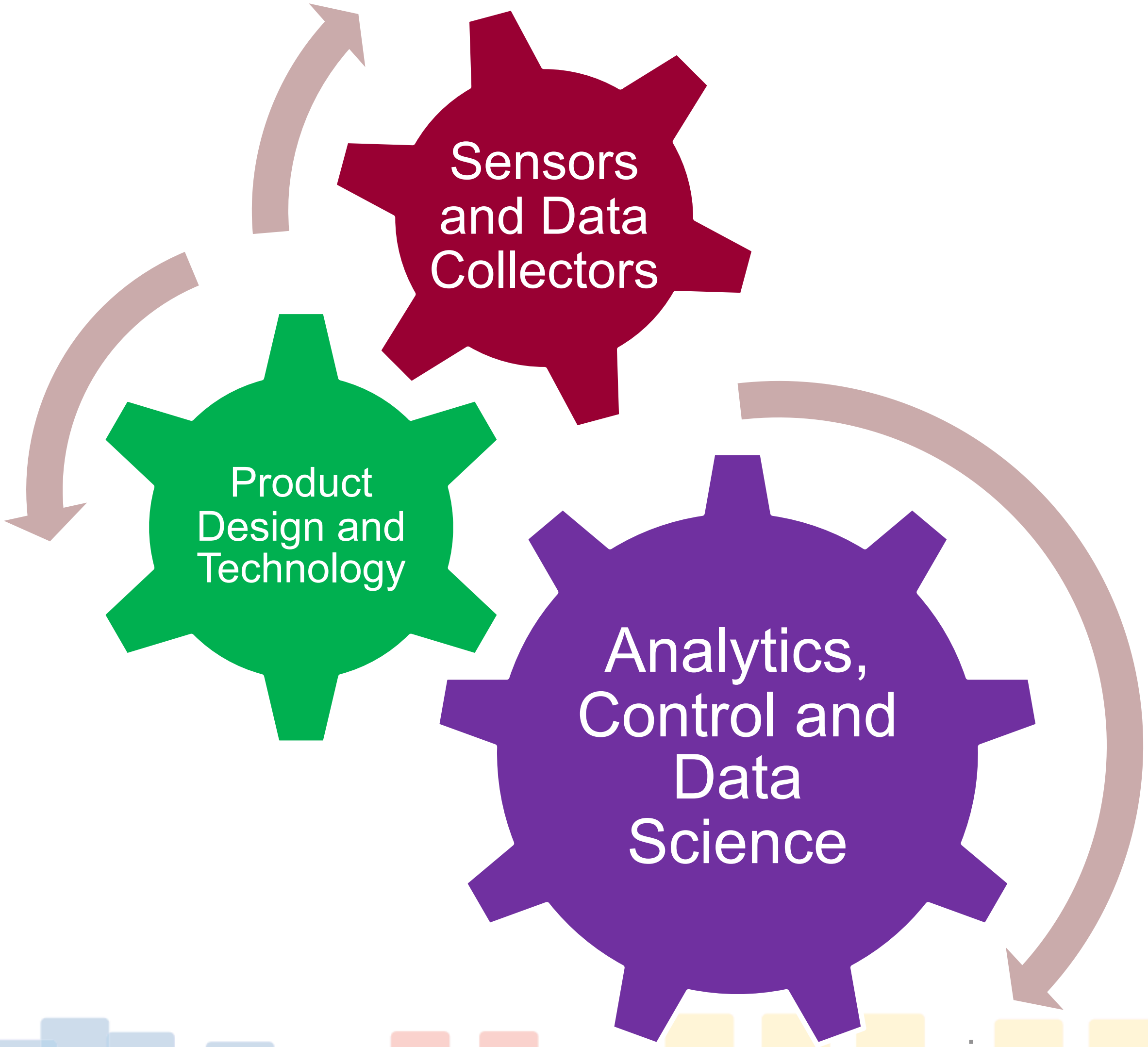
- *Virtually all systems* will have porous and ill-defined boundaries
- *Virtually all systems* will have ill-defined requirements which are changed frequently
- *Virtually all systems* will have access to many types and enormous numbers of external devices
- *Virtually all systems* will have access to enormous quantities of data, which have to be analyzed through data analytics to be of value

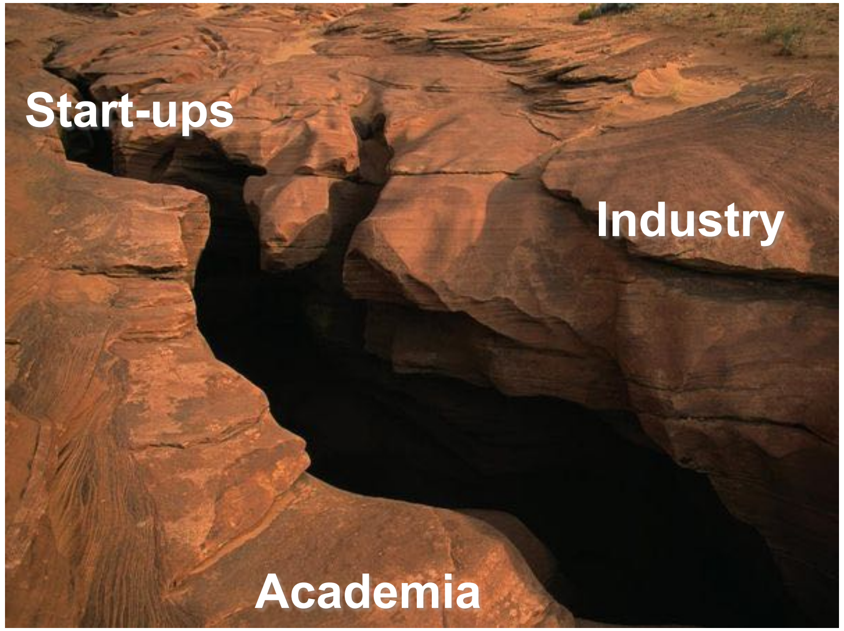
We are entering the Fourth Industrial Revolution



Source: Siemens AG

What is Industry 4.0?





“We stand on the brink of technological revolution that will fundamentally alter the way we live, work, and relate to one another. In its scale, scope, and complexity, the transformation will be unlike anything humankind has experienced before.”

Klaus Schwab
Founder and Executive Chairman,
World Economic Forum

Monitoring and Improvement in the Fourth Industrial Revolution

- Key enablers will move *performance* to a new and higher level
  - Big data
  - Data Analytics
  - Artificial Intelligence
  - Augmented Reality
  - Technology
- *Performance* here should be taken in the widest and systemic sense, from operational, economic, and market-related aspects to process/product/system safety/reliability and environmental

- Up to now, the detection and diagnosis of process failures and anomalies dominated process control
- Advanced sensing technologies advanced analytics fuel an important shift to *prognosis* of processes and systems, which will enable us to *predict* the health of systems far beyond the preventive approaches

Assessing the Maturity Level
of the Changes Implied by the Fourth Industrial Revolution

- Taking a CMMI-like approach to assessing the maturity level in the area of Advanced Manufacturing and Engineering

- Strategy and long-term planning
- Human resources
- Communication with customers and the market
- Processes in manufacturing
- Processes in engineering
- Business processes
- Processes in maintenance
- Logistics processes
- Processes in the supply chain
- Processes in product life cycle
- Information and knowledge management
- Processes in cyber assurance
- Investment in infrastructure and equipment
- Actual improvement outcomes and results

Integrating Dependability with Systems Engineering

- In order to meet the challenges of the Fourth Industrial Revolution we need to integrate dependability, resilience, and other ‘ilities with systems engineering:
  - Use the opportunities of the new era, like Big Data analytics, Prognostics and Health Monitoring (PHM), and modeling and simulation

Software Cybernetics

- How can we adapt software behavior, software processes, or software systems to meet basic and expanded objectives in a changing environment?

Software Cybernetics (cont.)

- Study software and its environment from a control theory perspective
- View software and its environment as a system, and software as a controller and/or communication media of the system
  - Such a system could be a production plant with IoT and advanced control mechanisms
  - At this level, the challenge in advanced manufacturing is how to design and implement optimal and/or stable systems

Software Cybernetics (cont.)

- The development of software and its environment involves many software tools, organizations, physical devices, and equipment
  - It forms a complex system and its product is also a complex system
  - Different software development methodologies employ different control and communication mechanisms and strategies
  - Software cybernetics is focused on the control and communication in such a "system" and its behaviors
    - Many research efforts on software engineering belong to this level

Software Cybernetics (concl.)

- At the highest level, software cybernetics evaluates software/IT technology as a big, dynamic, and evolving sociotechnical system
- Ask ourselves:
  - Why do some technologies and methodologies survive while others become extinguished?
  - Is there a law of evolution as in the natural biology system?

Modeling the Evolution of Technologies

- In the Fourth Industrial Revolution, we encounter rapid technology changes, and this approach can be a powerful business tool for predicting change cycles based on data, and it can be a support decision tool for companies and disruptive technologies developers

Modeling and Simulation for Systems Engineering

- Modeling and simulations are an essential part of the Fourth Industrial Revolution and the goal of *data-driven* and *evidence-based* systems engineering

Modeling and Simulation for Systems Engineering (concl.)

- Advantages and benefits for systems engineering in the new era:
  - They are the only “truth” on system parameters and behavior
  - They are based on data analytics and also create valuable data through simulations
  - They are also the only source of manufacturing systems
  - They can automatically create system software code
  - They support and ease the possible changes along the systems lifecycle
  - They also are used for preparing the operation and training material for the system
  - Exploiting the principle of *Digital Twin*

Twining

Design and virtual production

Real production

Computer Aided Design/ Engineering/ Manufacturing (CAx)

Digital development of products

Collaborative Product Data Management (cPDM)

Global collaboration across the entire value chain

Digital Manufacturing (DM)

Simulation of production processes

Manufacturing Execution Systems (MES)

Complete overview of the manufacturing process

Command & Control (C&C)

Steering and control of individual manufacturing steps

PHILIPS
Drachten

- Defects from 5-15% to below 1%
- Costs down by at least 20%
- Material and energy consumption improvement by at least 20%
- Number of finishing operations down by at least 35%

Twining

Computer Experiments

- The complexity of the mathematical models implemented in computer programs can, by themselves, build equivalent sources of random noise
- In complex code, a number of parameters and model choices gives the user many degrees of freedom that provide potential variability to the outputs of the simulation
- An experimental error can be considered in the statistical analysis of computer experiments
- Real-world phenomena are, often, too complex for the experimenter to keep under control by specifying all the factors affecting the response of the experiment
- Even if it were possible, physical measuring instruments, being not ideal, introduce problems of accuracy and precision. Perfect knowledge would be achieved in physical experiments only if all experimental factors could be controlled and measured without any error

Effective Risk Management

- Are current risk management methods effective in developing, deploying, and operating complex systems?
- Soon, many of the risks will come from the system's context and not from inside the system itself.

Effective Risk Management (cont.)

- The standard matrix that exhibits likelihood vs. consequences can be misleading. A risk with an infinitesimally low likelihood could provide disastrous effects
- Risk management is traditionally practiced using subjective assessments and scenario-based impact analysis.

Effective Risk Management (concl.)

- One of the major challenges of risk management in the modern era are *Black Swans*, a highly improbable event with three principal characteristics:
  1. It is unpredictable
  2. It carries a massive impact
  3. After the fact, we concoct an explanation that makes it appear less random, and more predictable than it was
- Why do we not acknowledge the phenomenon of Black Swans until after they occur?

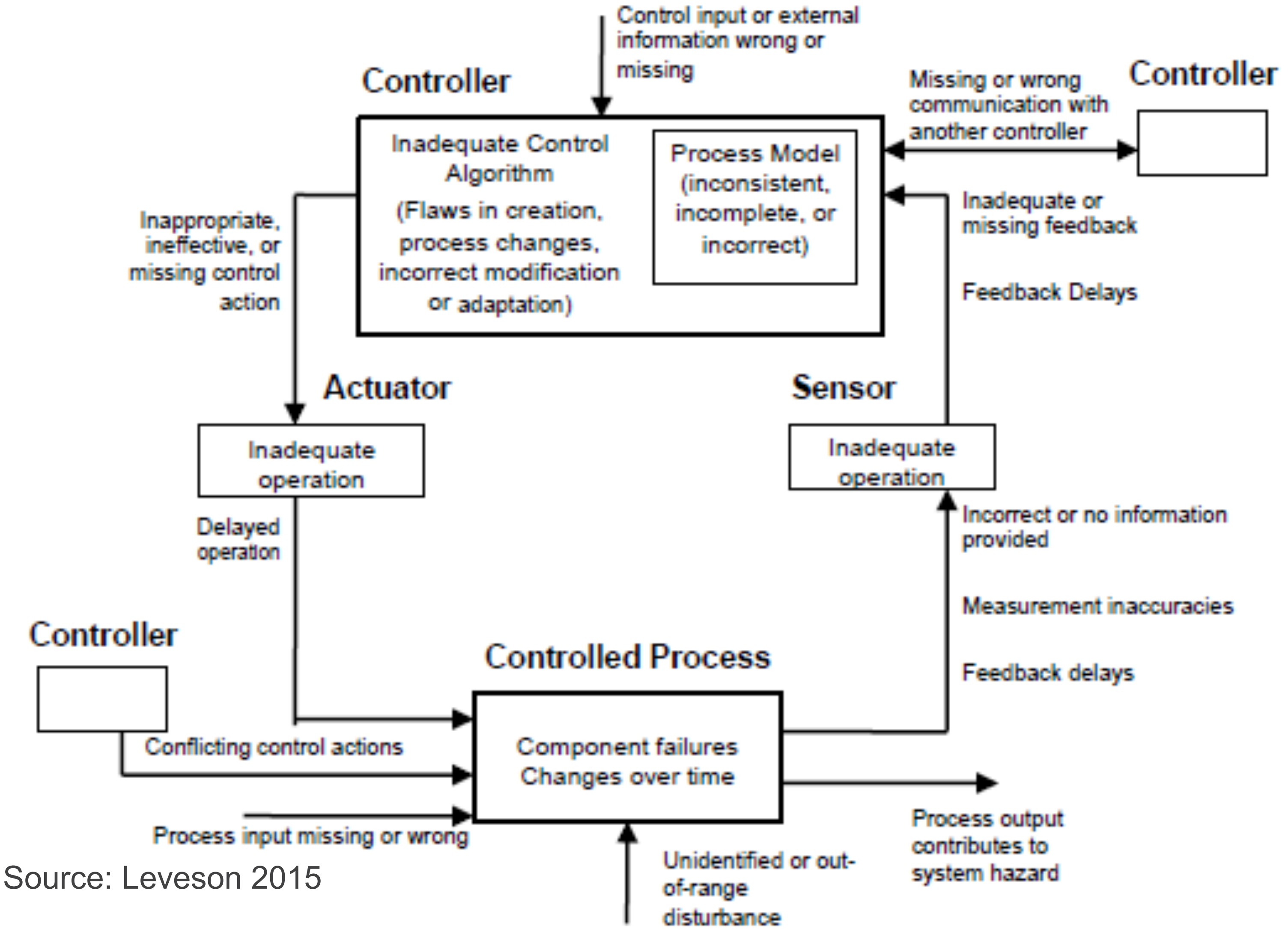
An Integrated Approach to Safety and Security Based on Systems Theory

- The Fourth Industrial Revolution creates innovative autonomous systems like driverless vehicles, drones, and multipurpose robots
- Prof. Leveson and her team at the MIT have developed a Systems Approach to Safety Engineering (STAMP)

The STAMP Model

- The principles of the STAMP model include:
  - Treat accidents as a control problem, not a failure problem
  - Note that accidents are more than chain of events, they involve complex dynamic processes
  - Prevent accidents by enforcing constraints on components, software behaviors, and interactions

Identifying Causal Scenarios



Source: Leveson 2015

The STAMP Model (concl.)

- The systems developed, deployed, and operated in the Fourth Industrial Revolution are complex and software-intensive, use the cloud very extensively, apply Big Data, and feature autonomous, robotic, and IoT capabilities, so they are highly vulnerable to safety and security threats
- The integrative approach of safety and security engineering based on the STAMP model through systems engineering is essential for the success of systems in the new era

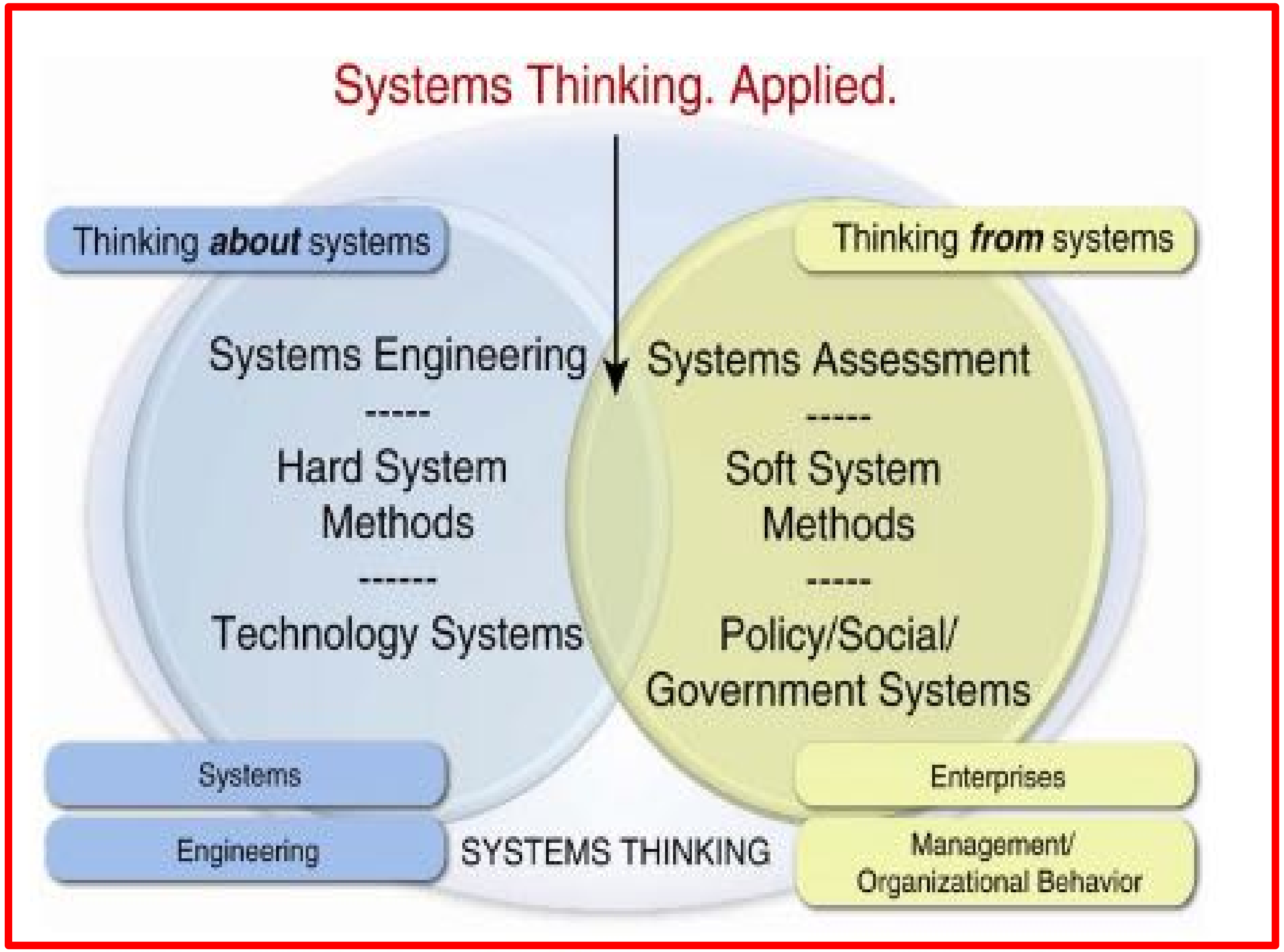
INCOSE VISION 2025 in View of the Fourth Industrial Revolution

- INCOSE VISION 2025 did not fully anticipate the velocity, breadth, and depth of the Fourth Industrial Revolution; *there is a need for "out of the box" systems engineering and thinking*
- Opportunities like Big Data , Data Analytics and AI should result in a vision that leads to *Evidence-Based and Data-Driven Systems Engineering*
- Software and IoT intensive systems should be addressed more deeply
- The challenges of the advanced "ilities" like Dependability, Safety, and Security should be incorporated into the systems engineering discipline as a great opportunity

Applied Systems Thinking

- Systems Thinking focuses on how a system interacts with the other constituents of the larger system of which it is a part and with all aspects of that larger context.
- *The importance of Systems Thinking in the new systems environment cannot be understated*
  - Virtually all systems will soon operate in a broad context that transcends the usual boundaries, extending to the involvement of science and engineering, computation and communication, and myriad social, legal, cultural, environmental, and business factors

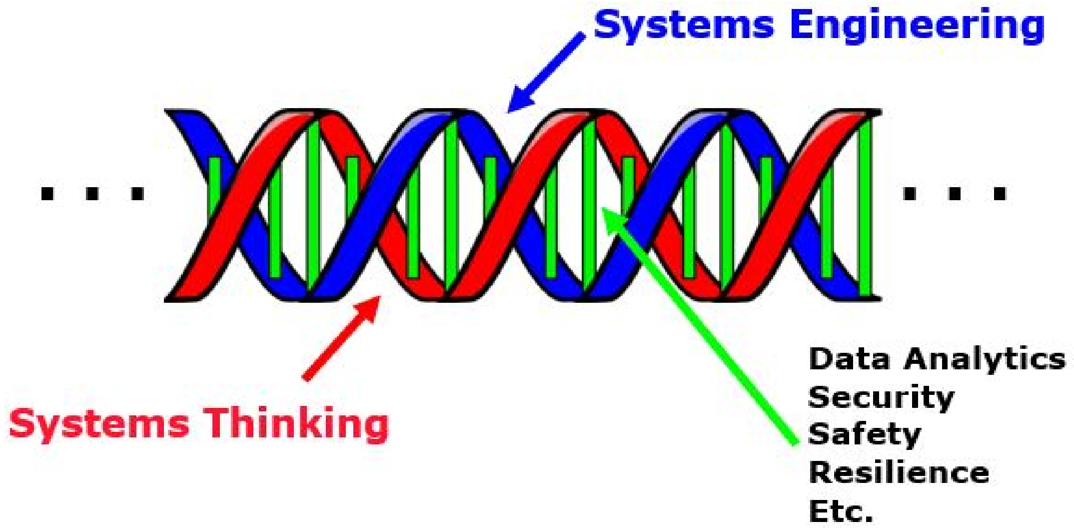
Applied Systems Thinking



Advanced Systems Engineering

- Advanced Systems Engineering is needed to accommodate the challenges and opportunities of the Fourth Industrial Revolution
- The Fourth Industrial Revolution presents large challenges to the "traditional' systems engineer, to be sure
  - These include: unanticipated behavior, lack of centralized control, cyber security, scalability, sustainability, resilience, dependability, growth, and the definition and management of interfaces and communication channels
  - Most of these problems, however, can be viewed as opportunities, too.

- On the basis of the above challenges, we suggest that there is a need for a new model based on the double helix



- This model emphasizes the tight connection that Systems Engineering must have with Systems Thinking, as well as the new properties and processes, such as data analytics, security, safety, reliability, risks and resilience, that must be integrated into the process

A New Edited Book on Advanced Systems Engineering

Title: ***Systems Engineering in the Fourth Industrial Revolution: Big Data, Novel Technologies, and Modern Systems Engineering***

Editors: **Ron Kenett, Robert S. Swarz, and Avigdor Zonnenshain**

Publisher: **Wiley**

Preliminary Table of Contents

1. The Fourth Industrial Revolution and its challenges & opportunities for systems engineering
2. The role of analytics in the design phase
3. The role of fast prototyping in the development process
4. The role of analytics in the testing phase
5. Monitoring & improvement of advanced industrial processes
6. Prognosis Health Monitoring (PHM) & Conditioned Based Maintenance (CBM)
7. Integrating advanced reliability engineering into systems engineering (dependability, trustworthiness)
8. An integrated approach to safety & cyber security based on system theory
9. Effective & evidence-based risk management
10. Applied systems thinking
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12. Human systems Integration (HSI) in the smartphone era
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17. Applying systems engineering in start ups
18. Future outlooks on methods and tools of advanced system engineering
19. Education of advanced system engineers for the new era
20. Protection of personal information

Final Words

- We propose Smart Systems Engineering for Smart Ecosystem & Smart Systems
- Is this an opportunity or a threat to the Systems Engineering discipline?

Questions?


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