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Systems Engineering 2.0

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Director, CoSE
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My Background

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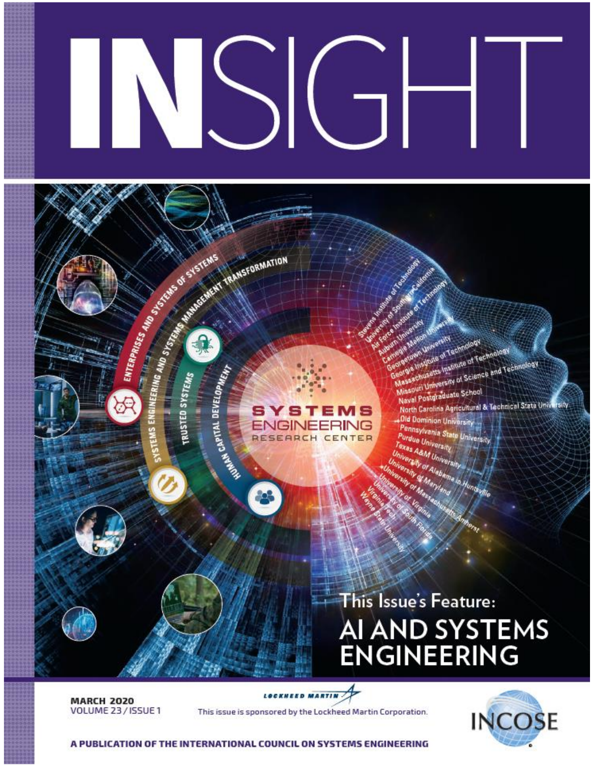
Systems Engineering 2.0 for AI-Intensive Learning Systems

- Systems engineering is ill-prepared for AI-intensive, evolving, learning systems
- The OODA loop and all its agents need to be *inside* the system
- New systems abstractions, interfaces, and practices are necessary to address these changes

- **Systems are limited by systems engineering capability, not technology.**

This situation is reminiscent of VLSI systems engineering in the mid-1970s



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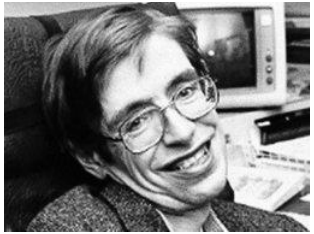
Why Systems?

Source: INCOSE Vision 2025



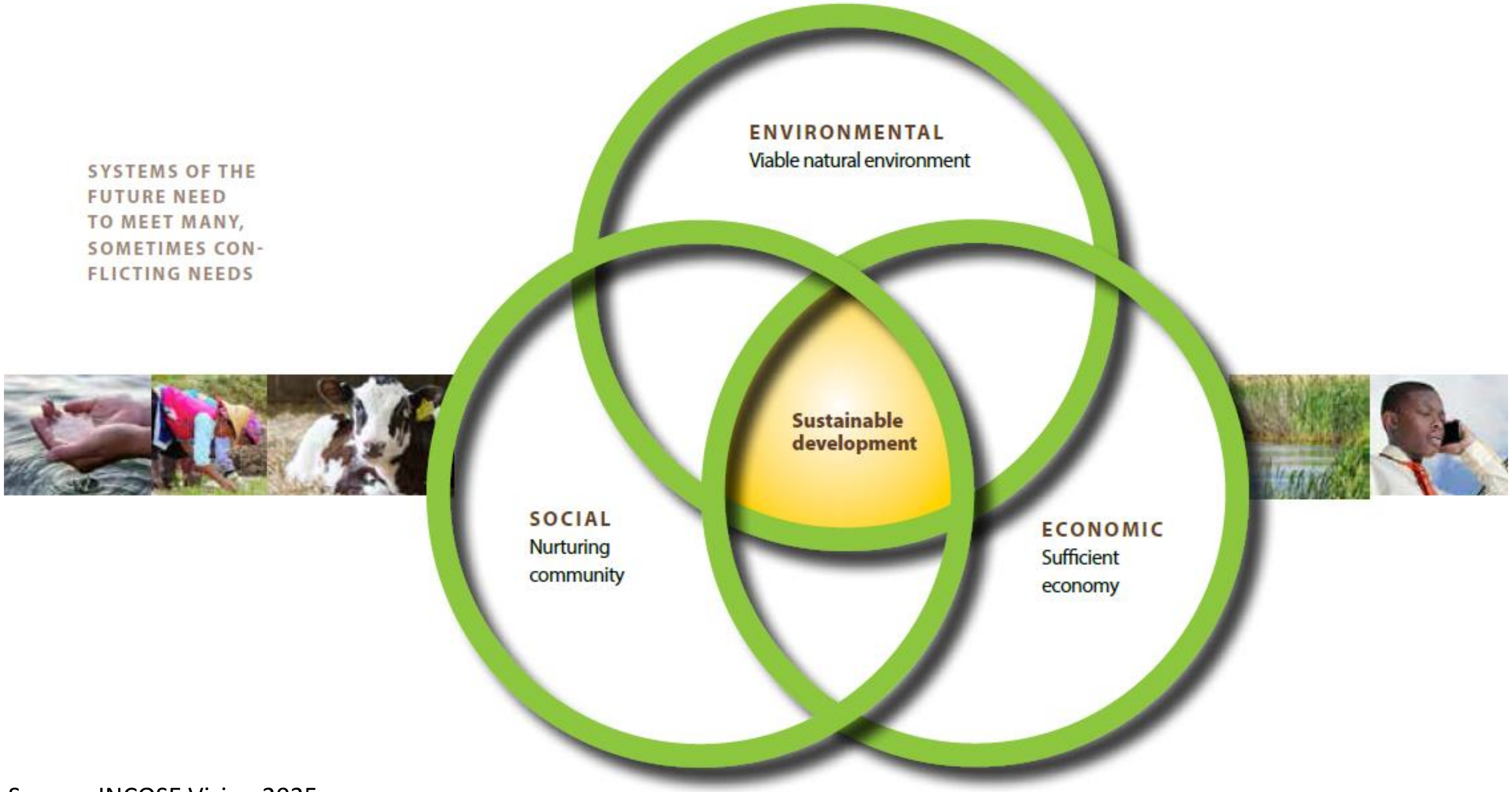
"I think the next century will be the century of complexity"

Impact:

- All systems decisions makers are systems thinkers
- All engineers have systems engineering skills
- All systems engineers are broad-based leaders

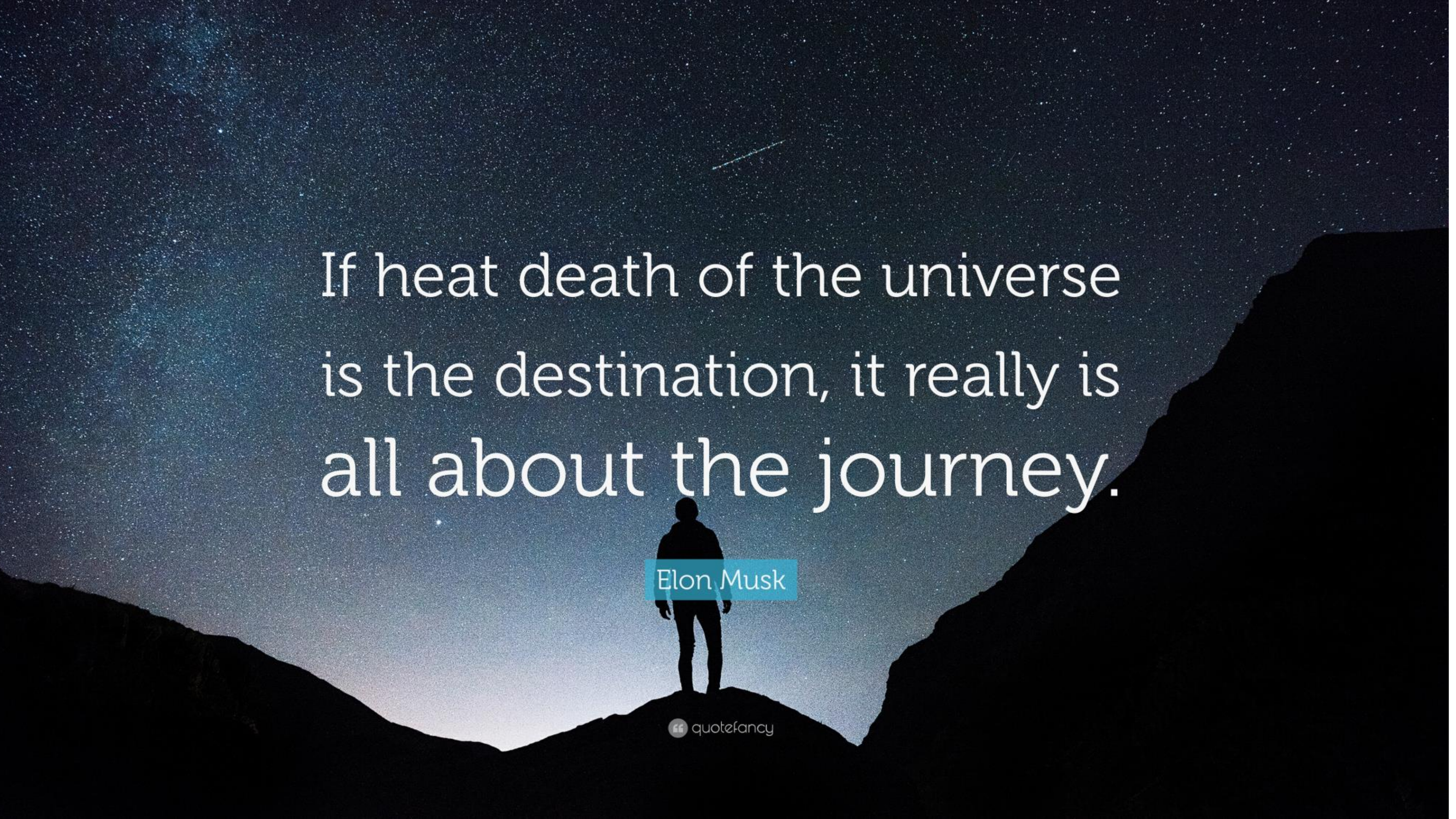
System Trends

Stakeholder Expectations Drive System Trends



Source: INCOSE Vision 2025

0. There is a game
1. You can't win
2. You can't break even
3. You can't even get out of the game


If heat death of the universe
is the destination, it really is
all about the journey.
Elon Musk
quotefancy

Self-organizing Complexity

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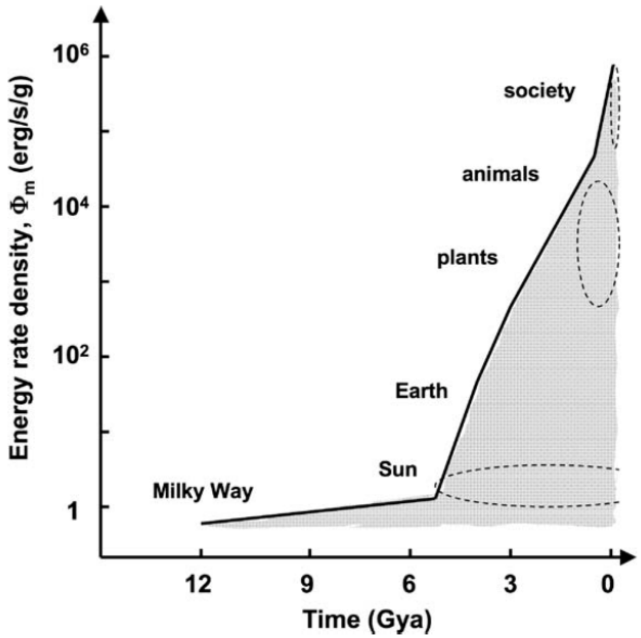
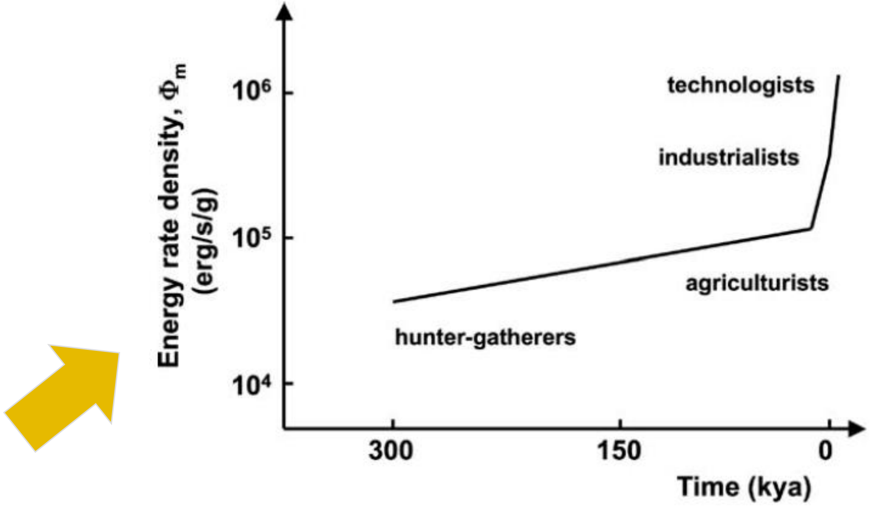
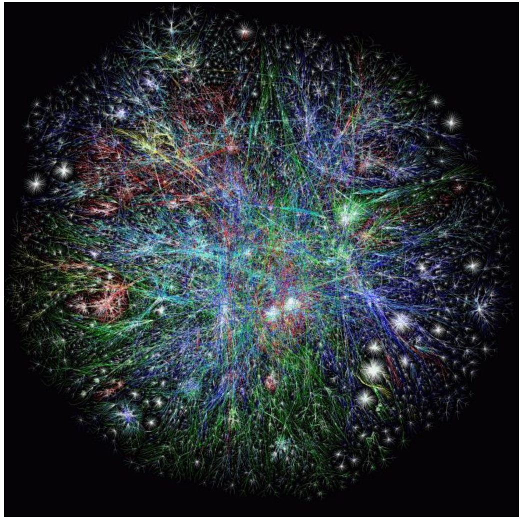


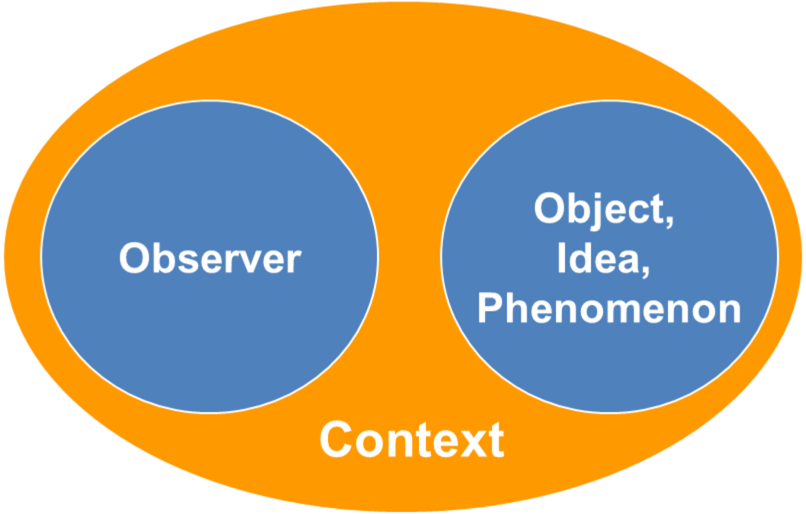


Source: "Energy Rate Density as a Complexity Metric and Evolutionary Driver", E. J. CHAISSON Wright Center and Physics Department, Tufts University, Medford, Massachusetts and Harvard College Observatory, Harvard University, Cambridge, Massachusetts.

What is Complexity?

"the degree of difficulty in accurately predicting behavior over time"

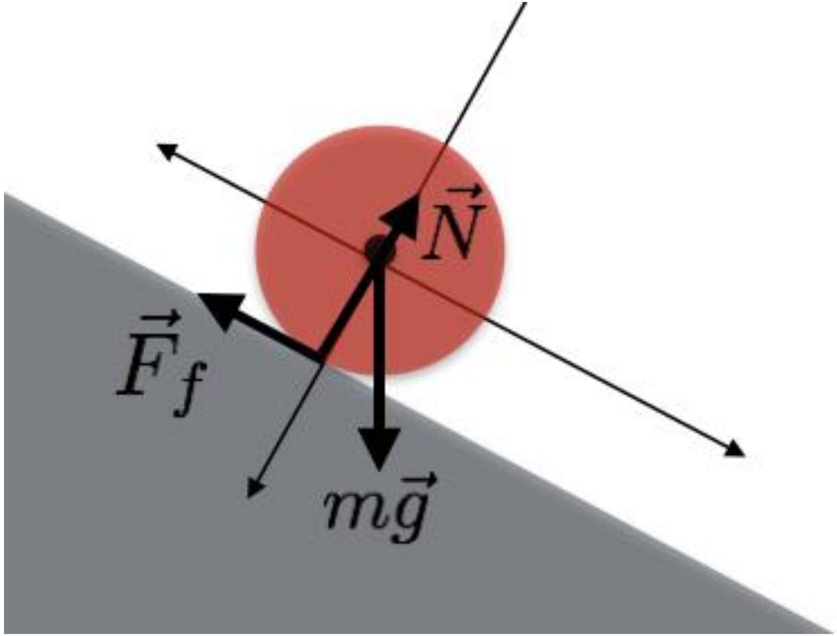




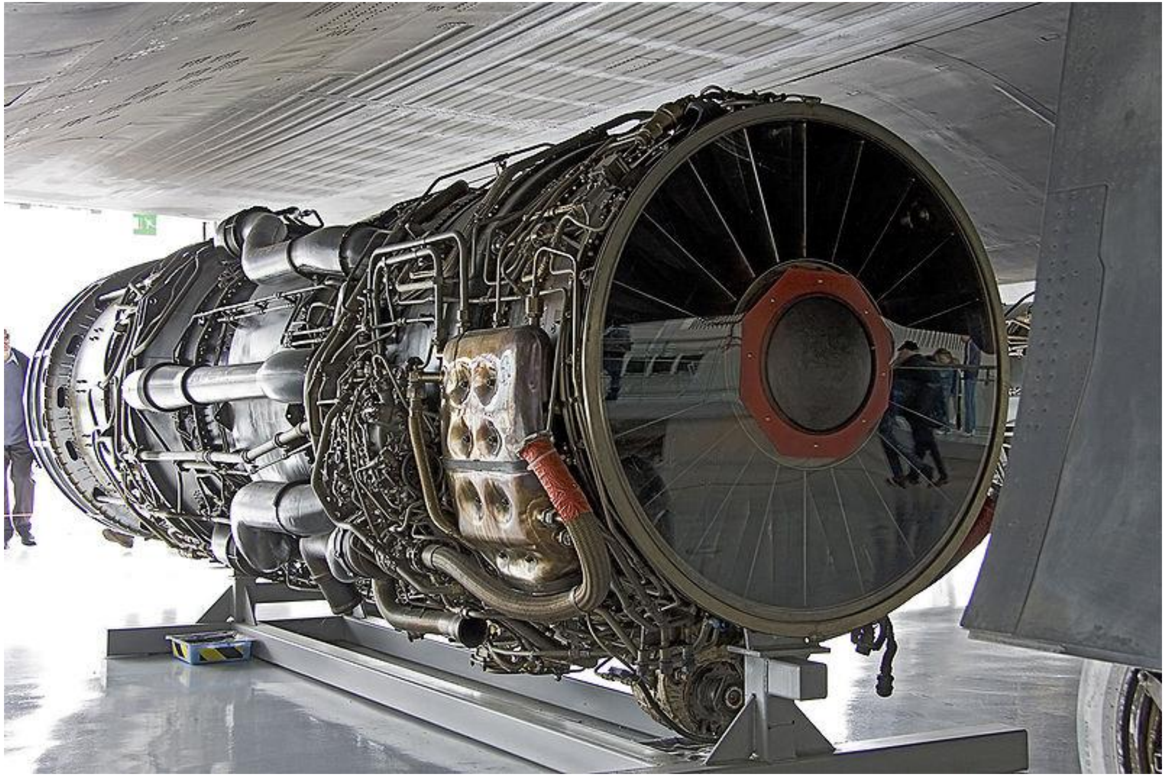
It’s more than just numbers…

- 25K protein coding genes: humans
- 45K protein coding genes: rice
- 7M lines of code: fighter plane
- 30M lines of code: cell phone
- 100M lines of code: automobile
- 2,000M transistors: PC CPU chip
- 10^{27} molecules: gas in room

This is simple



This is complicated



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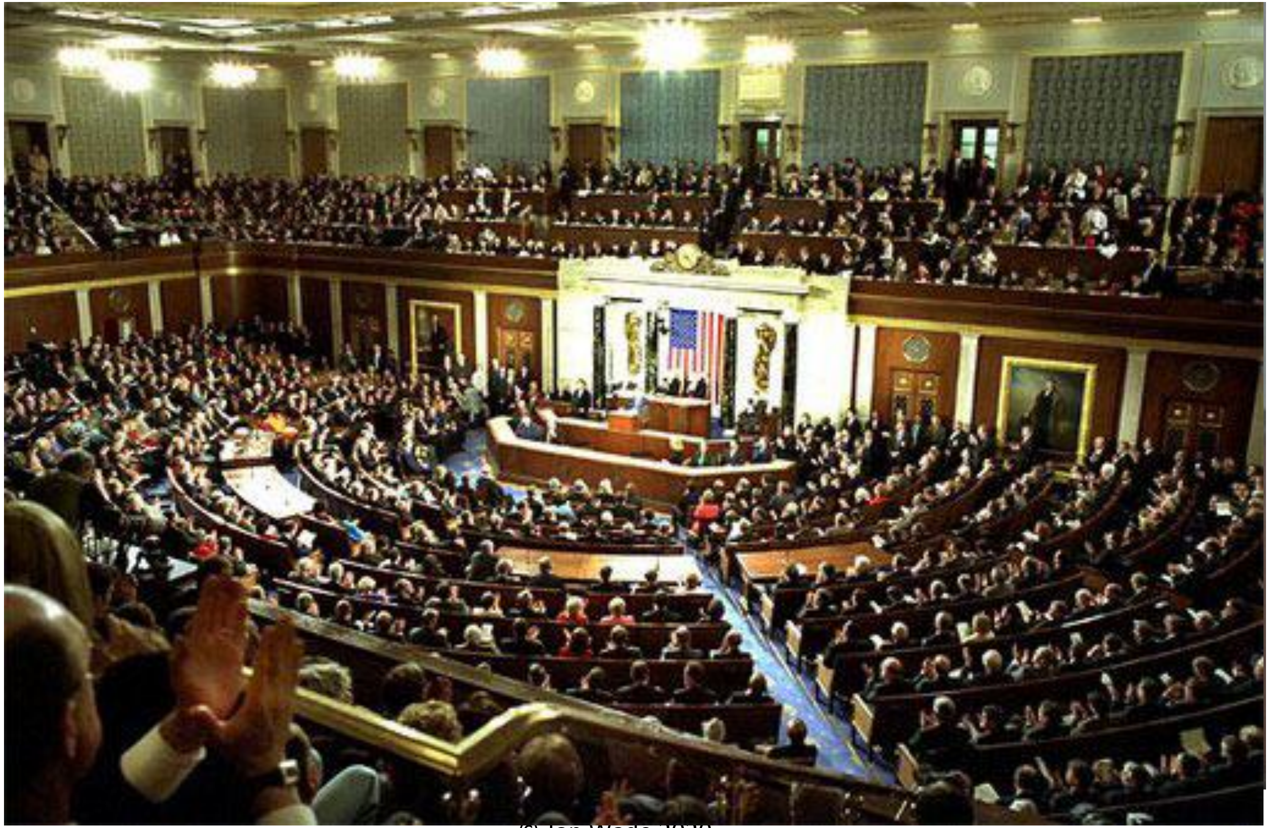
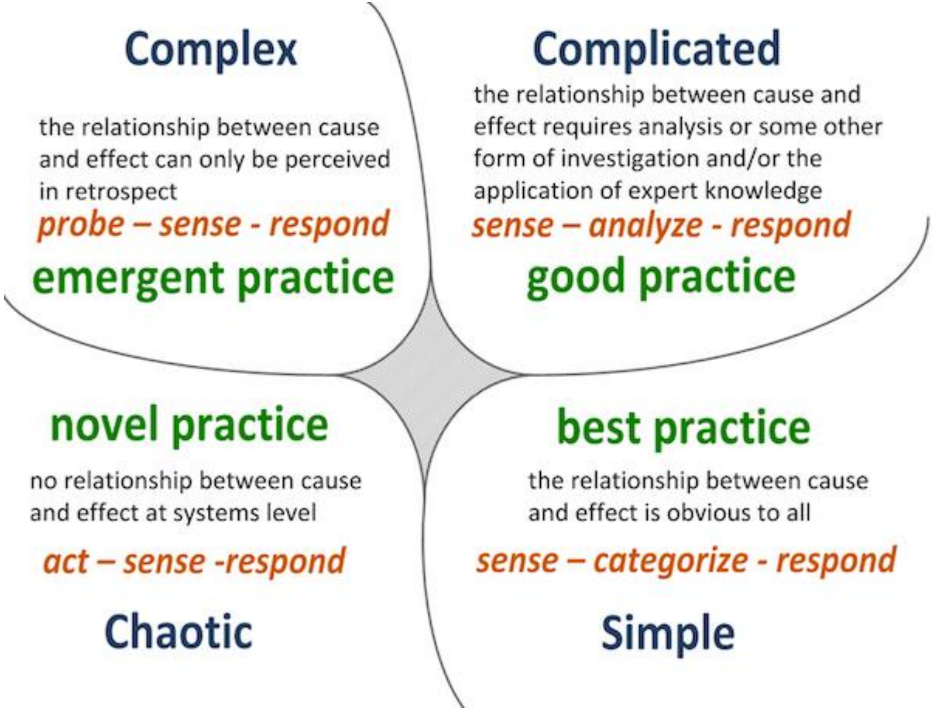
This is Complex

This is chaotic



System Types



Cynefin Framework (source: Kurtz & Snowden)

Growing Levels of System Complexity

Increasing complexity, cumulative ambiguity, “lack of control”

Cynefin Framework

Source: INCOSE Vision 2025

Software-free Cars

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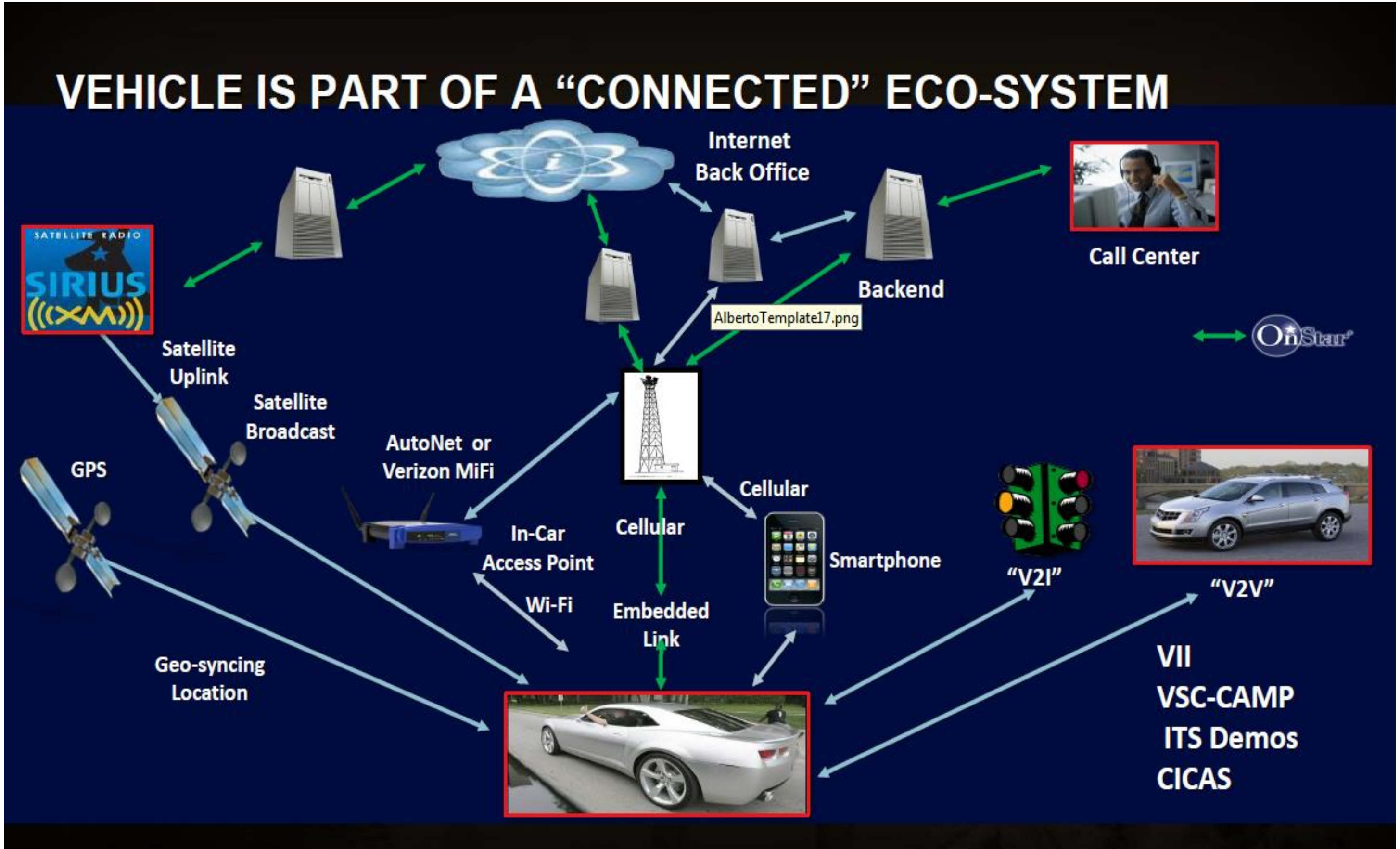
Automobiles: Cyber-Physical Systems



Source: Alberto Sangiovanni-Vincentelli, EE249 Course

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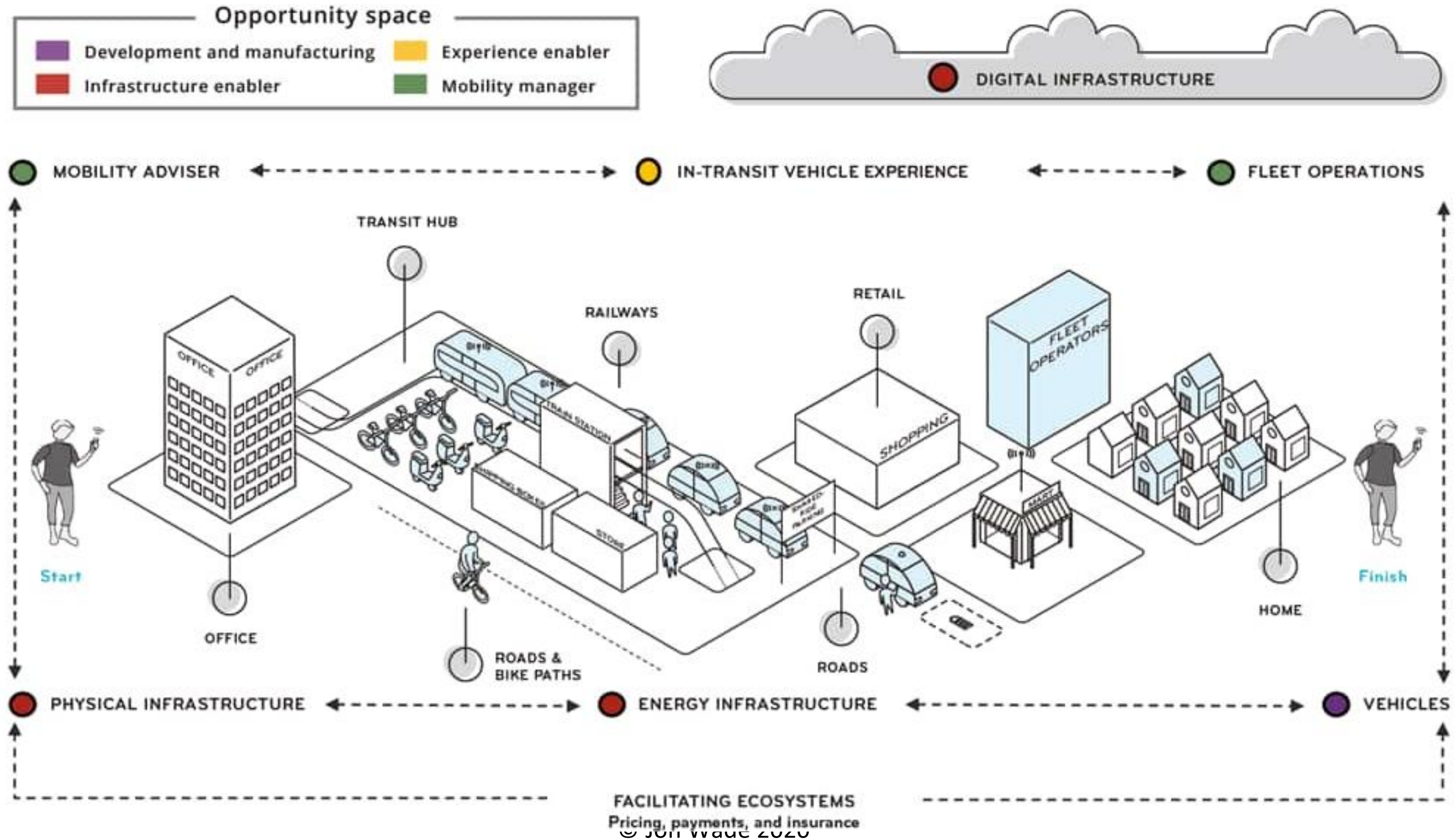
The Future Mobility Ecosystem



Accelerating Rates of Change

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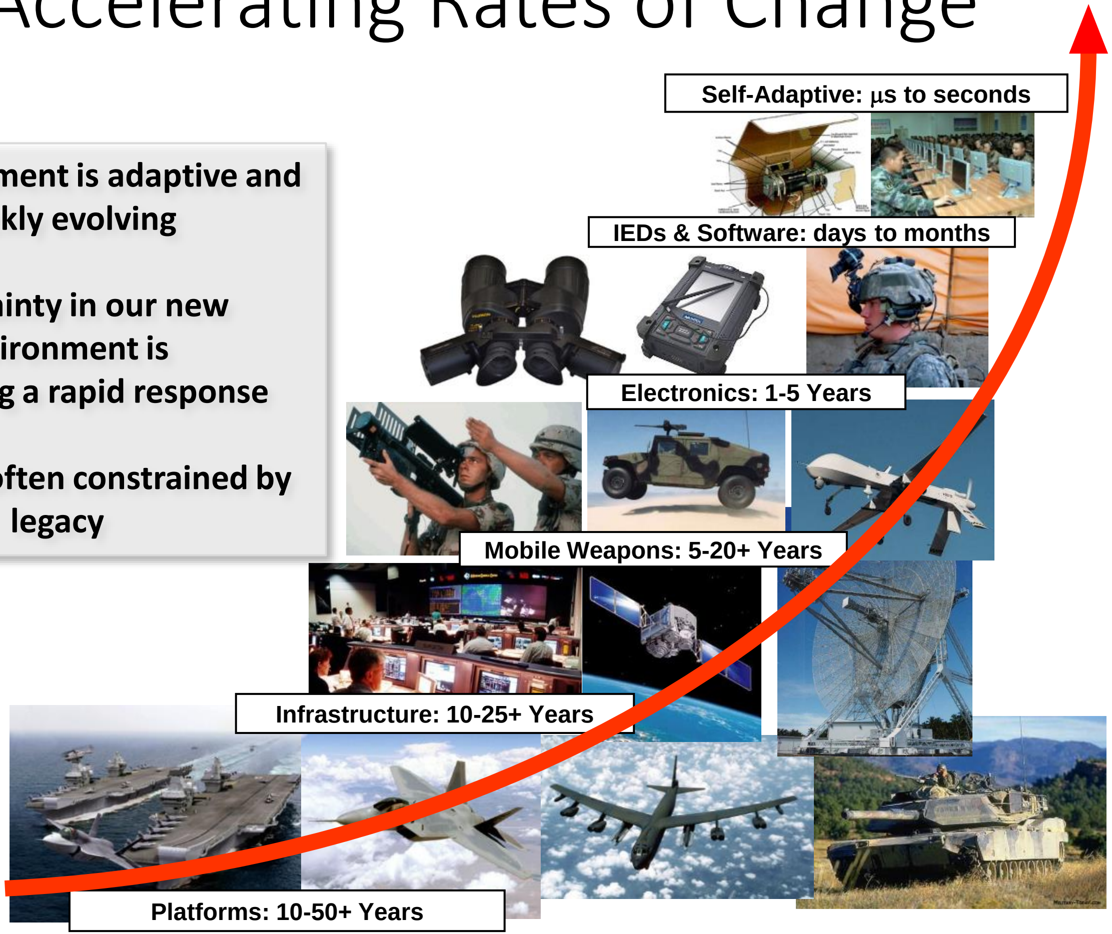
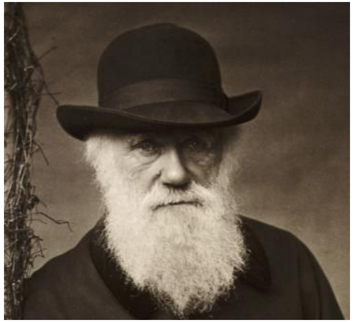
The environment is adaptive and quickly evolving

Uncertainty in our new environment is demanding a rapid response

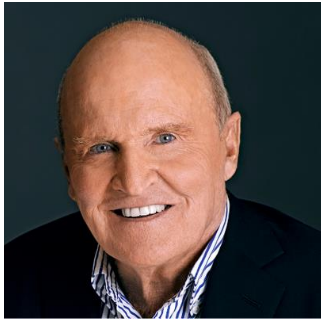
Yet we are often constrained by legacy



Rate of Change



Adaptability is Key to Survival



It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is most adaptable to change.

– Charles Darwin

If the rate of change on the outside exceeds the rate of change on the inside, the end is near.

– Jack Welch

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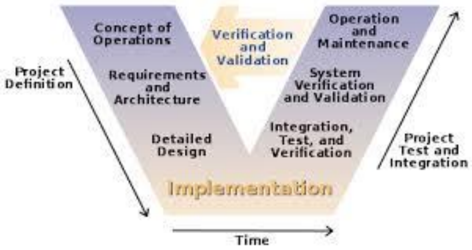
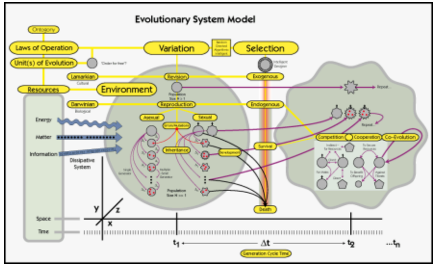
The Transition





From: Systems Engineering 1.0

- Systems built to last
- Opinion-based decision making
- Paper-based documentation
- Deeply integrated architectures
- Hierarchical organizational model
- Satisfying the requirements
- Phase-based Verification & Validation

To: Systems Engineering 2.0

- Systems built to evolve
- Data-driven decision making
- Simulation-based documents
- Modularized architectures
- Ecosystem of partners
- Constant experimentation and innovation
- Continuous Verification & Validation

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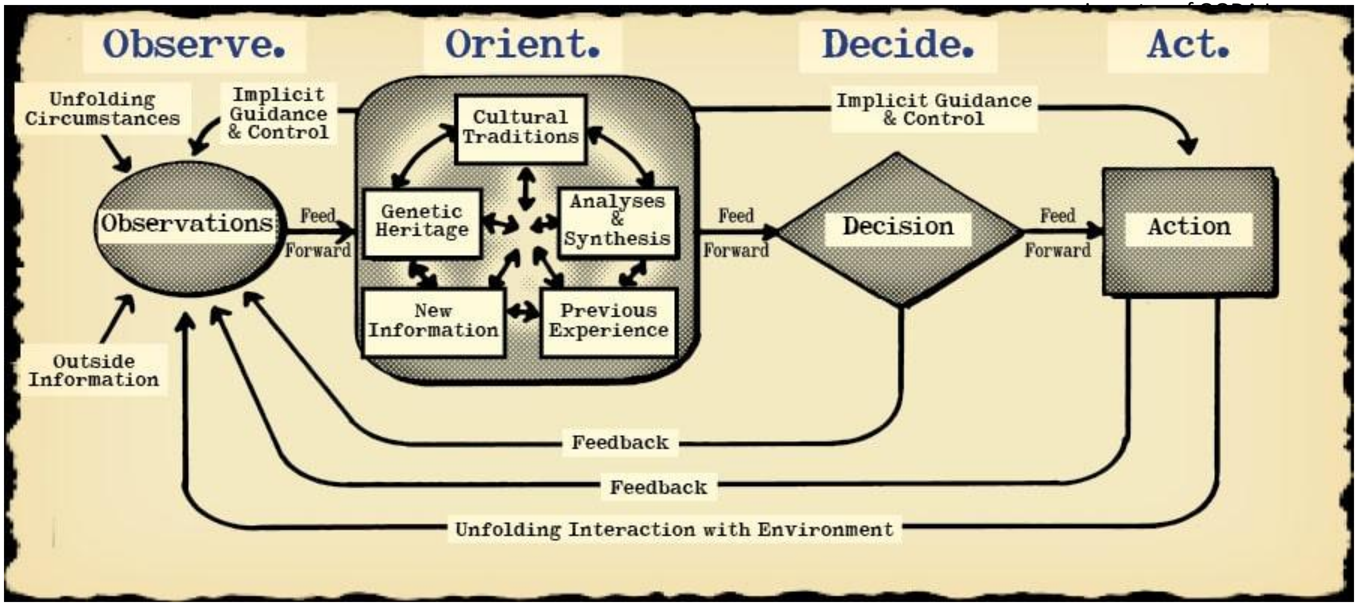
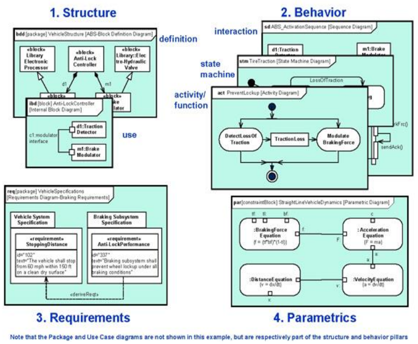
Transition from Open-Loop to Closed-Loop Systems

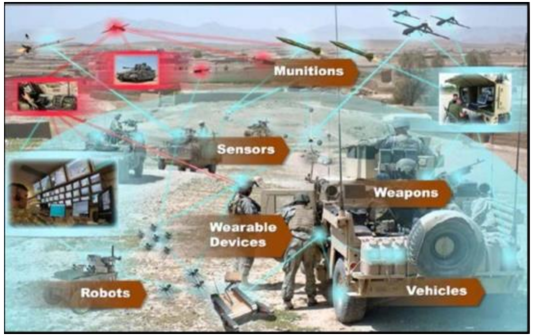
Col. John Boyd, fighter pilot, “40-second Boyd”,



The Power of Digitalization: extracting value from data

Exploiting the digital power of
computation, visualization and communication
to take better, faster actions



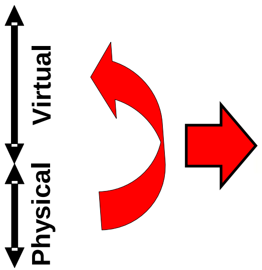


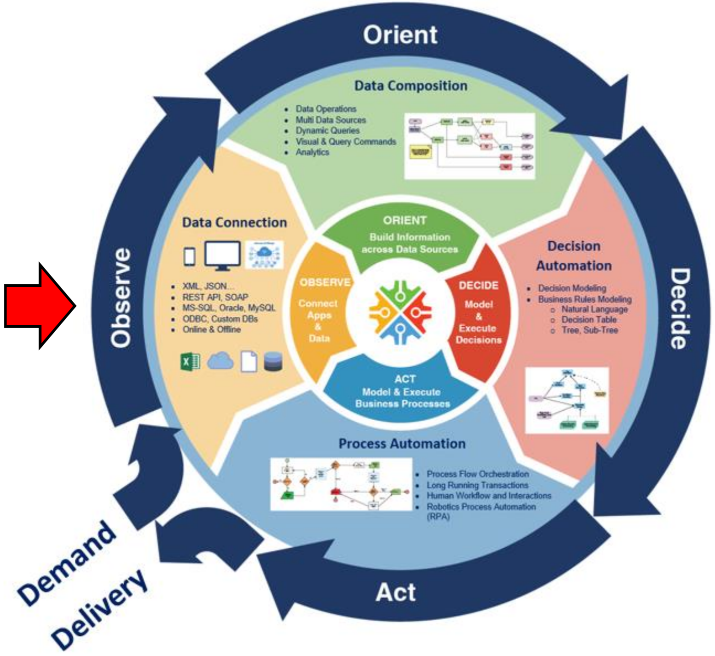
- Simulated data

- Experimental data

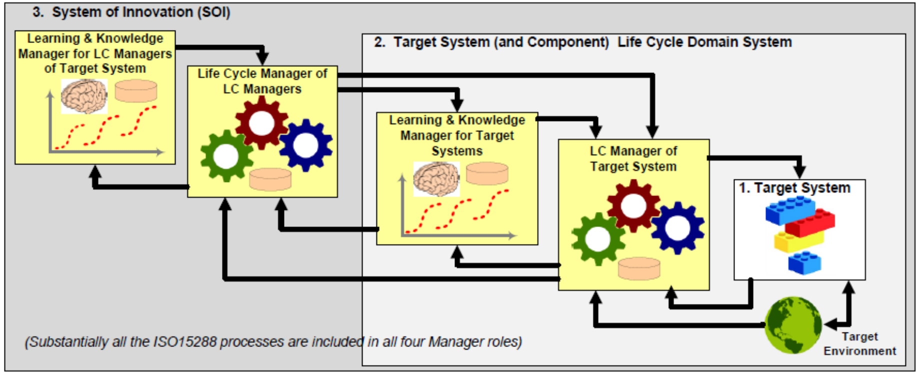
- Observed data

Dynamic System Validation





Agility is Critical:
Continuous Learning System Engineering



1. **Agile Software Development** – agile development limited software

2. **Agile System Development** – Entire organization is agile, reducing the risk in any particular interval

3. **Continuous Deployment** – System can be updated at any time, DevOps blurs boundary between development and operations

4. **Systemic Learning** – System is used as an environment to conduct experiments and learn

5. **Continuous Learning System** – System autonomously conducts experiments for system optimizations and/or guides experiment decision-makers and concept designers

Based on Jan Bosch's "Stairway to Heaven"

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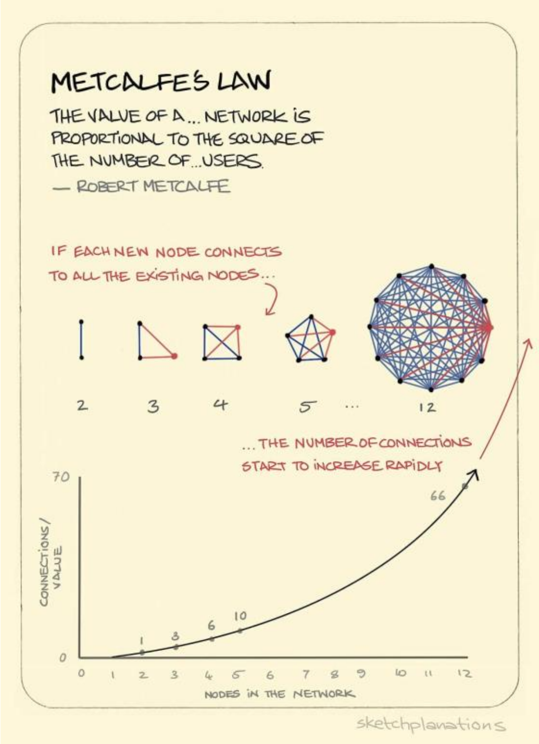
INCOSE Response: Systems Engineering

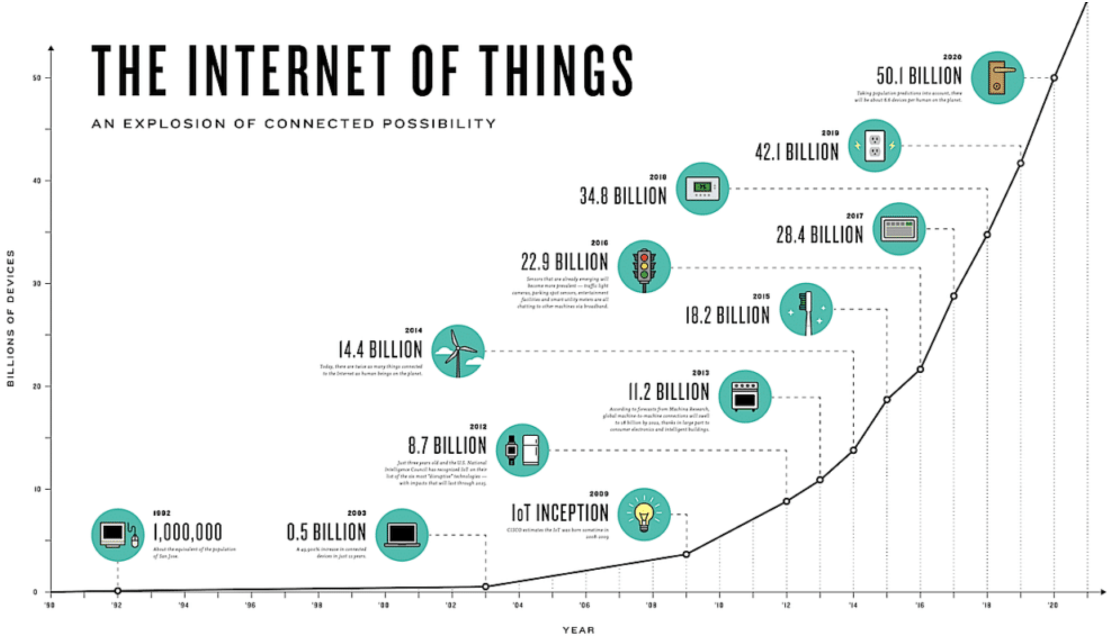
Ends: The ability to create systems that continually evolve to meet their customers' needs under their timelines while being trustworthy, economical and sustainable.

Means:

1. Develop and implement SE Methods, Processes and Tools (MPTs) that are relevant to complex/non-deterministic systems
2. Create expertise of evolving systems (e.g., architectural archetypes) that are appropriate for the domains of interest
3. Ensure that we have a workforce that is capable of applying these MPTs to the systems of interest
4. Broadly apply the systems approach to a broad set of domain areas and scales

The Power of the Network





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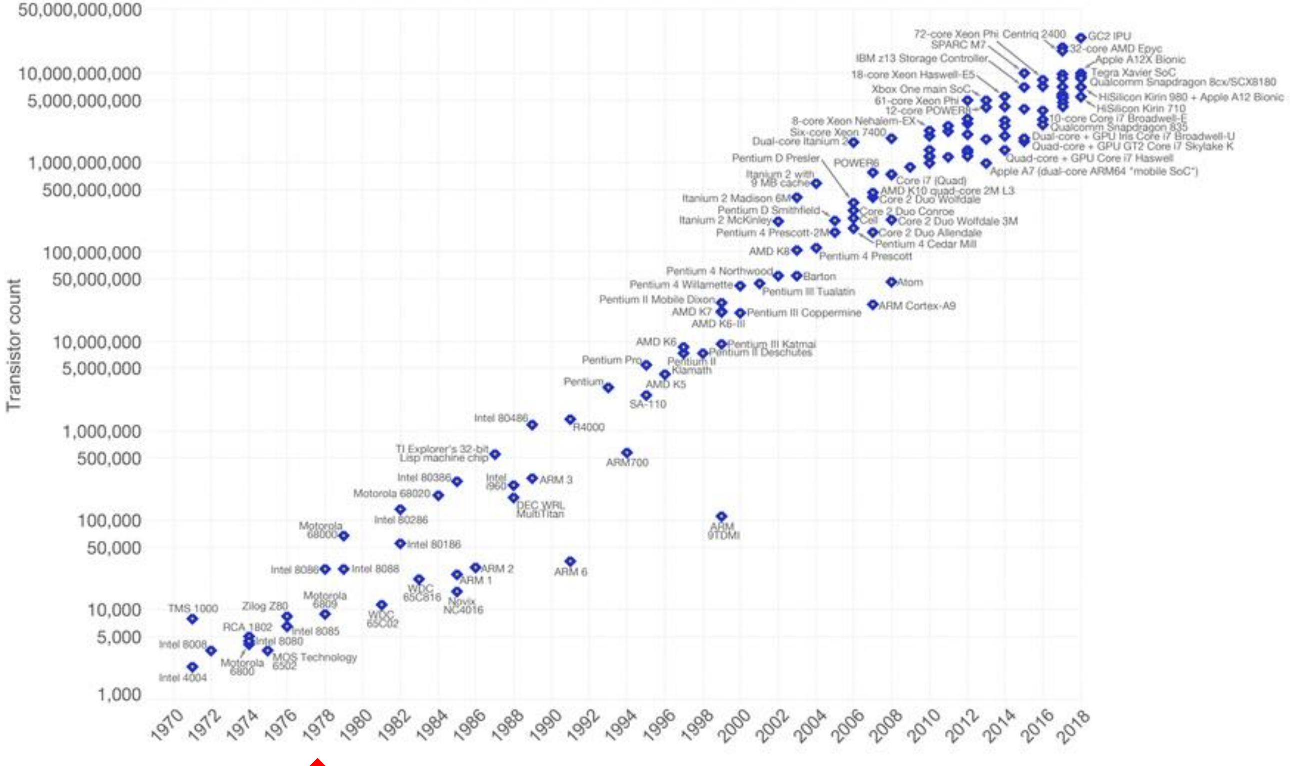
Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

First MicroProcessor Intel 4004

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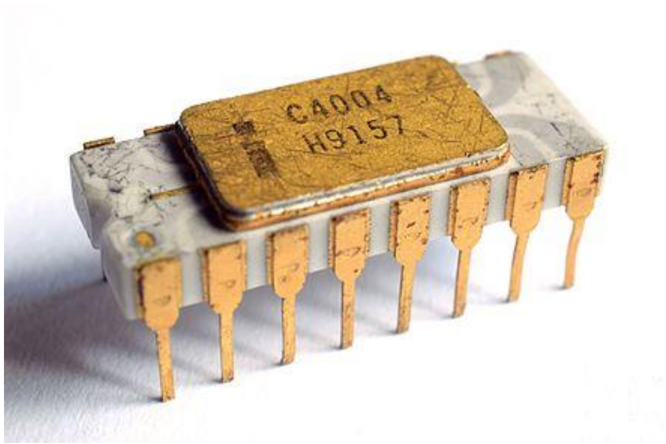

General Info

Launched	late 1971
Discontinued	1981

Performance

Max. CPU clock rate	740 kHz
Data width	4 bits
Address width	12
RAM	640 bytes
Min. feature size	10 µm
Transistors	2,250
Successor	Intel 4040

While architecturally simple, the 4004 design implementation and fabrication details were obscure to most computer scientists.

According to Lynn Conway, the question back then was ‘‘whether the design of VLSI systems would be possible outside Intel moving forward’’.
VLSI was limited by engineering, not by technology.

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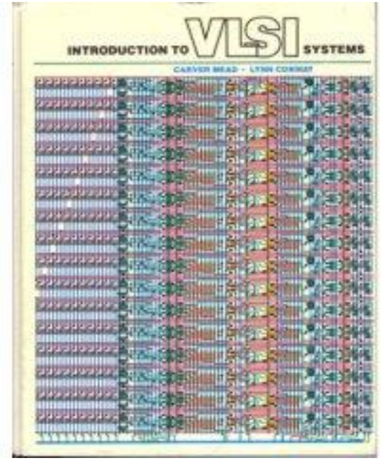
The Mead Conway Revolution

Applications – Software Engineering
Binary Code – Computer Science
Architecture – Computer Science
Logic – Computer Science
Circuits – Electrical Eng
Device Models – Electrical Eng
Device Properties – Device Physics
Material Properties - Material Science



The Power of Abstraction
For VLSI - 1979

Mead Conway Impact

Mead & Conway’s methods were suddenly brought forward in 1978–1980 and made visible through a set of courses reaching 120 universities within two years.

Concepts such as simplified design methods, new, electronic representations of digital design data, scalable design rules, ‘‘clean’’ formalized digital interfaces between design and manufacturing, and widely accessible silicon foundries suddenly enabled thousands of chip designers to create tens of thousands of chip designs.

A completely new way of creating VLSI systems on silicon was born.

Moore’s Law was unimpeded by engineering capability.

Key Lessons from Mead & Conway

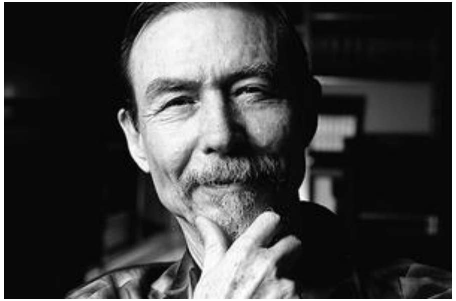
“Thirty years later what has remained the same includes: (1) the importance for interdisciplinary approaches to research and development, (2) the continuous quest for new vertically-integrated scalable design methodologies, and (3) the need for open standards and interchange procedures that foster innovation by enabling collaborative engineering across institutions and beyond geographic constraints.

…they have formed a bridge between the two fields overcoming traditional boundaries that had until then confined device physics and integrated circuit design to EE departments and digital system architecture to CS departments.” - Prof. Luca Carloni, Columbia University, USA

“meta principles are the pillars of its success over the years, namely simplification, interdisciplinarity, collaboration and orthogonalization of concerns.” – Prof. Alberto Sangiovanni-Vincentelli

Panel: The Heritage of Mead & Conway, What Has Remained the Same, What Was Missed, What Has Changed, What Lies Ahead

Lynn Conway



Carver Mead

Path Forward

"the heritage of Mead & Conway lives on due to the continuous need to develop new vertically-integrated design methodologies, which requires reinventing the stack of levels of abstractions to tame design complexity while unleashing performance scalability."

"While it is impossible to predict exactly what lies ahead, the role of open standards, intermediate formats, interchange procedures, and automation tools will be instrumental in an increasingly interdisciplinary and collaborative environment."

- Prof. Luca Carloni, Columbia University, USA

Panel: The Heritage of Mead & Conway, What Has Remained the Same, What Was Missed, What Has Changed, What Lies Ahead

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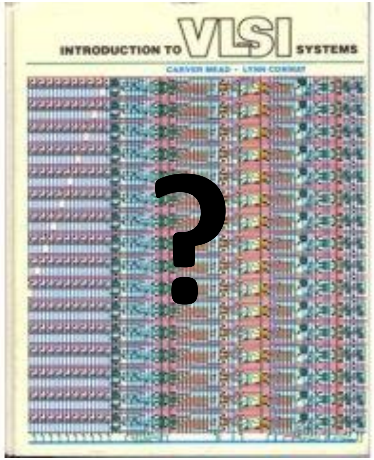
The AI-Intensive System Stack

Understanding Value Chain – Systems Thinking	**Closed-Loop Continuous Improvement Systems Engineering**
Determining Critical Data – Systems Eng	
Collecting Data – Data Science	
Engineering Features/Outcomes – Data Science	
Setting Up Training Data – AI/CS	
Choosing and training Algorithm – AI/CS	
Determining HW Platform – Computer Eng	
Validating & Deploying AI System – Systems Eng	



The Power of Abstraction
For AI Systems - 2020

Education as Living Research Lab

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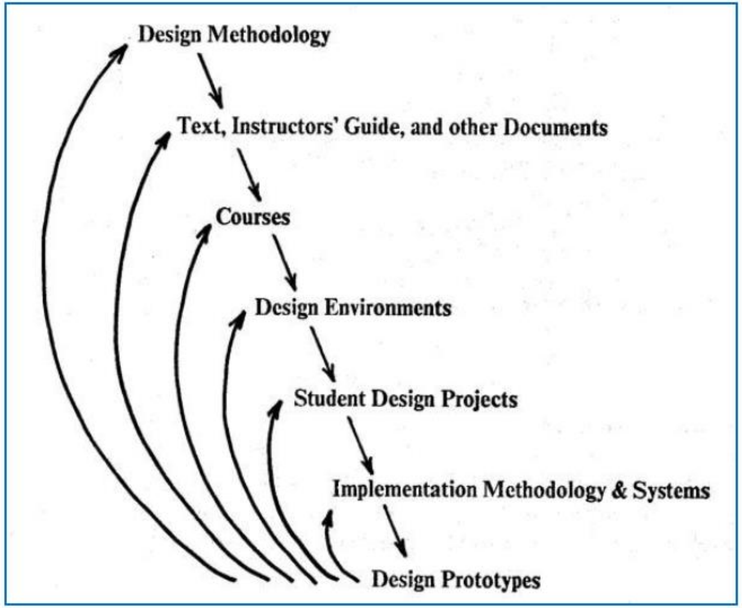

FIGURE 17: The evolution of a multi-level system of knowledge: design projects provide feedback for debugging at all levels [28].

Lynn Conway, MPC Adventures: Experiences with the Generation of VLSI Design and Implementation Methodologies, 1981

Future Work

There is much work to be done…

- Develop new vertically-integrated scalable design methodologies
- Define layered abstractions with orthogonalized concerns
- Create open standards and interchange procedures that foster innovation by enabling collaborative multi-disciplinary engineering across institutions and beyond geographic constraints
- Write “the Book”
- Create the courses
- Start the revolution

Thank you, Lynn & Carver!

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Questions?