H·I·T·S Engineering

Towards a Theory of Systems Engineering

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Elements of a Good Theory

- A good theory captures a **domain** to provide **explanations**, and to allow **predictions**
- Formalization of a theory leads to **definitions**, **basic laws** (axioms, basic principles, basic narratives), and **derived laws** (theorems, extended narratives)
- To become culturally effective, a good theory needs to be **teachable**, and **learnable**

Main Concern

What makes up a good theory of systems engineering?

- **Step 1:**
  Analyzing the current status of systems engineering as a theory

- **Step 2:**
  Defining basic elements of a theory of systems engineering

Content

- Introduction
- Systems Engineering as a Theory Today
- What is Wrong with Systems Thinking?
- A Short Review of the Philosophy and Science
- The Scope of Systems Engineering
- A Model of Semantic Memory
- Three Essential Systems Engineering Narratives

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Systems Engineering as a Theory Today

- The Domain to Which Systems Engineering is applied
- Explanations
- Predictions
- Definitions
- Teachability and Learnability

The Domain to Which Systems Engineering is applied

- Systems engineering evolved in large, complex, and innovative governmental programs
  - As stakeholder, the government is involved over the complete system life cycle with a global interest in system life cycle efficiency
  - Development-on-Demand following a planned economy approach
  - Systems Engineering addresses the challenges regarding stakeholder orientation and multi-disciplinary engineering

- With basic technologies invented becoming affordable, they started to penetrate the whole economy
  - With some delay the demand for multi-disciplinary engineering follows

- INCOSE claims universal applicability of systems engineering, and has invested in industrial outreach since more than ten years
  - However, the codification of systems engineering has not been adopted to market-opportunistic modes of operation typical for a market economy

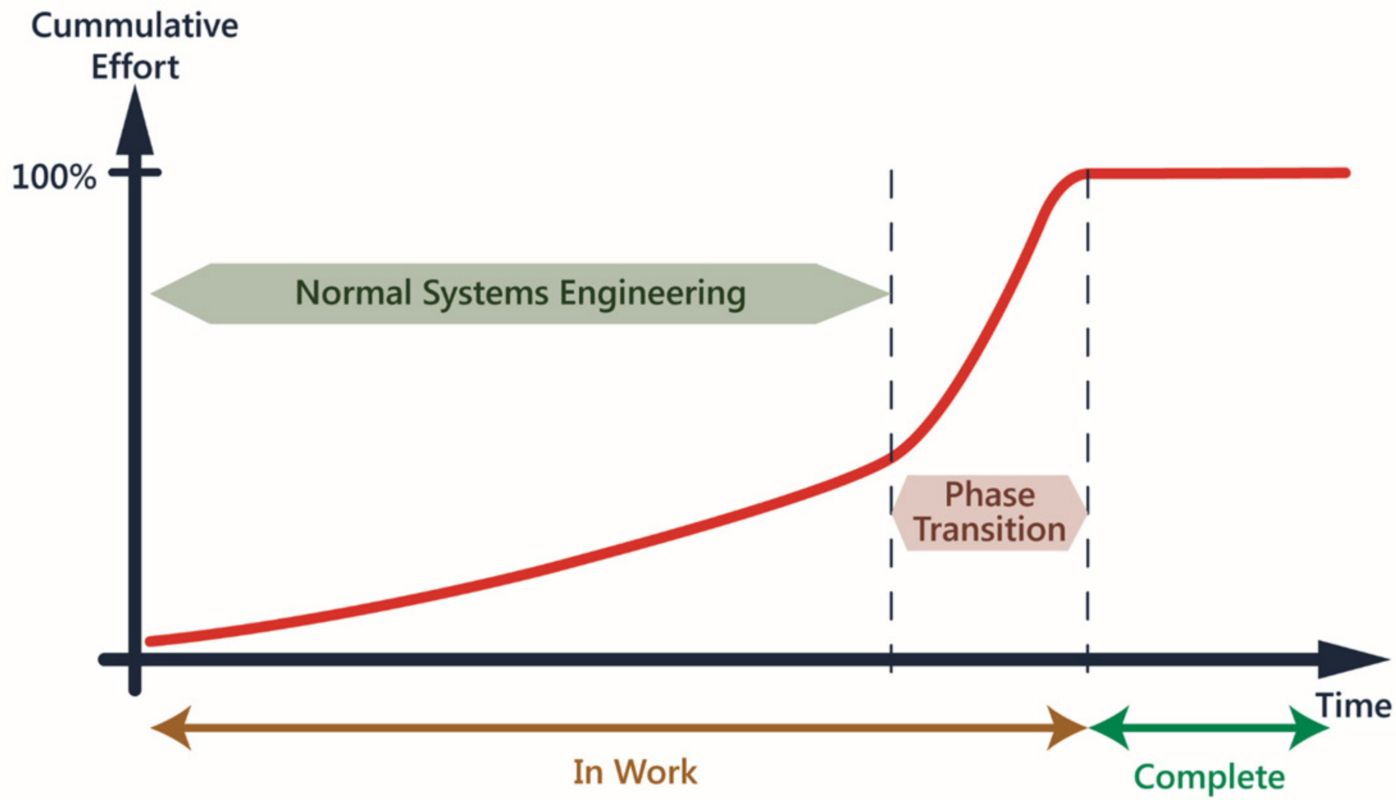
Explanations

- Systems engineering is especially employed for explanation
  - before a project is commenced, and
  - in case of project failure

- In the latter case, the following failure causes are identified usually
  - Late requirement changes
  - Entering subsequent system life cycle phases with immature inputs

- In consequence, this reasoning
  - envisions a normal case that may be applicable when doing similar projects applying the same technologies, processes and tools again and again, and
  - ignores the importance of continuous learning typical for systems engineering endeavors developing advanced and innovative products and services
  - In conclusion, the normal case in real life is deemed to be abnormal

Predictions



- As long as the phase transition between in-work and complete requires a high effort, reliable prediction capabilities of systems engineering applied to advanced and innovative products and services are out of reach

Definitions

- The definitions within ISO 15288:2015 are partly inconsistent, and incomplete
  - In majority, they have been taken from other standardization domains, for example ISO 9000
  - They are partly adopted to their specific usage in the scope of systems engineering – sometimes not considering the wider impact
- *Example 1*
  - The terms Requirement, Validation, and Verification are borrowed from ISO 9000 with altering the definition for Requirement, and distorting the meaning of Validation – according to the definition – as a further verification activity
- *Example 2*
  - The term enterprise is missing in ISO 15288:2015 in favor of the more general term organization following again the ISO 9000 conventions
  - Thus, systems engineering remains widely ignorant of the legal entities with their specific duties regarding liability, social responsibility etc.

Teachability and Learnability

- Theories, as complex as they may be, need to be broken down into comprehensible and interconnected narratives for becoming teachable
- Theories connected to existing knowledge and experience are better learned,
  - especially if they may be seamlessly integrated into existing knowledge and experience
- For an unprepared mind, learning from theory is rarely successful
  - Then, long-term exposure gaining personal experience is required for comprehension, and adopting a theory as a guideline for personal behavior
- Teachability and learnability of systems engineering is severely challenged by
  - the standard approach to try to teach systems engineering in a single narrative
    - Too many side stories clutter essential principles
    - Important topics like system interface engineering are not captured adequately
  - conflicts with tacit mental models about the philosophy of science

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Typical Elements of Systems Thinking

- Reference to Aristotle
- References to the social sciences
- Sets of golden rules

Reference to Aristotle

- Aristotle has dominated philosophy in the pre-scientific era
- Testimony for substantiating the claim for a long tradition of systems thinking
- Potentially motivated to compensate some topics not well captured by contemporary scientific thinking

Aristotle: Metaphysics

- How Aristotle is cited:
  - The whole is more than the sum of its parts

  or
  - The whole is greater than the sum of its parts

  or
  - 1 + 1 > 2 or 1 + 1 = 3
- What Aristotle has written:
  - „But then there is what is composed of something in such a way that the whole is one, in the manner not of a heap but a syllable – and the syllable is not the letters, nor are B plus A as the syllable BA, …"

    (Aristotle. Metaphysics, Book VII, Chapter 17. Translation by Joe Sachs, 1999.)

Do you notice the differences?

References to the Social Sciences

- Textbooks on systems thinking refer to the social sciences, but in the references books and papers on social sciences are rarely cited
- Social sciences are at least as fragmented as the engineering and natural sciences
- No integrative social science discipline with an easily comprehensible interface to systems engineering exists

Sets of Golden Rules

- Textbooks on systems thinking try primarily to verbalize and to record knowledge acquired tacitly
- The result is likely consisting of golden rules following a semantic
  - Do this because …
  - Do that because …
- As more elaborate the tacit knowledge as more golden rules will be exposed to the reader
- Interferences of the golden rules remain unconsidered
- Recipients are likely to fail the integration with existing knowledge and experience due to the short narratives established by golden rules
- The rules may confirm the convictions of people who are already convinced, but may fail to convert people with dissenting views

The Systems Thinking Acquisition Cycle

- The systems thinking acquisition cycle
  - In the past, systems engineers grew over time with the complexity of the products and services
  - In the course of their professional career they gained primarily tacit knowledge about systems thinking
  - Unexperienced engineers are unable to buy in into systems thinking on the basis of the stories told by the old guys
  - They have to spend decades to acquire the same knowledge about systems thinking – most of it tacitly – again

- It is irresponsible to demand from young engineers today to follow the same path again
  - Young systems engineers are faced with complex products and services requiring multi-disciplinary efforts up from the start of their professional career
  - There is a body of knowledge in systems engineering to shorten the adoption to today's professional challenges

Content

A Short Review of the Philosophy and Science

- The Invention of Science
- Positivism
- Behaviorism
- Logical Positivism
- Reductionism
- Critical Rationalism
- Further Developments

The Invention of Science

- Before the renaissance has triggered an era of discovery, the world had been understood as something stable with Aristotle as the primary reference

- Modern scientific terminology has matured by the end of the 17^{th} century
  - Facts – Experiments – Laws – Hypothesis/Theory – Evidence/Judgement

- From this foundation, the industrial revolution lift off exploiting natural laws

References:
David Wotton: The Invention of Science – A New History of the Scientific Revolution. 2015.

Positivism

- Auguste Comte (1789 – 1857)
  - No search for absolute truth
  - Reliance on observations, and understanding of dependencies between observations for bringing meaning into the world
  - Three stages of social evolution
    - Theological Stage – Metaphysical Stage – Positive Stage
- Ernst Mach (1838 – 1916)
  - Propagator of positivism applied as a research paradigm to physics, physiology and psychology
  - Influential to many successors: American Pragmatists – Vienna Circle

References:
Auguste Comte: Cours de Philosophie Positive. 1835. (German Translation, 2015.)
Cheryl Misak: The American Pragmatists. 2013.
Michael Stöltzner, Thomas Uebel (Editors): Wiener Kreis – Texte zur wissenschaftlichen Weltauffassung. 2009.

Behaviorism

- John B. Watson (1878 – 1948)
  - Founder of behaviorism as a radical positivistic endeavor
  - Claim to describe all behavior completely by stimulus/response mechanism
  - "In his first effort to get uniformity in subject matter and in methods the behaviorist began his own formulation of the problem of psychology by sweeping aside all mediaeval conceptions. He dropped from his scientific vocabulary all subjective terms such as sensation, perception, image, desire, purpose, and even thinking and mind as they were subjectively defined."
- Behaviorism became the dominant scientific approach in psychology in the US until severely challenged around 1960
- Even today some cognitive psychologist claim to stand in the tradition of behaviorism
  - continuity of method instead of continuity of research results

References:
John Watson: Behaviorism. 1925.

Logical Positivism

- Relativity theory and quantum mechanics provided a new boost for advancing the philosophy of science
  - Vienna Circle and Berlin Group
- Rudolf Carnap (1891 – 1970) took an exposed position claiming the unity of science based on a universal language capable to express everything consistently in a single language based on physics
- There is more evidence that such a language may be out of reach for humans
  - Kurt Gödel demonstrated for the Principa Mathematica that some theorems remain undecidable
  - Experience of translators between natural languages

References:
Rudolf Carnap: Die physikalische Sprache als Universalsprache der Wissenschaft. 1932.
Rudolph Carnap: The Unity of Science. 1934.
Kurt Gödel: Über formal unentscheidbarer Sätze der Principa Mathematica und verwandter Systems. 1931.
Juri Lotman: On the Semiosphere. 1984. English translation 2005.

Reductionism

- Reductionism is closely related to logical positivism
- Reductionism may mean a number of things
  - Generating knowledge means going into detail making new distinctions
  - If the details are understood, the whole is understood as well easily
  - All translation issues between discipline specific languages are uniquely determinable
- Applied to engineering, reductionism also justifies the preference of applying the simplest models and solutions that ensures that intended objectives are achieved
- In consequence, reductionism denies emergence
  - For generating meaning, knowledge has to be put into context

Critical Rationalism

- Karl Popper (1902 – 1994) – also from Vienna – was not directly involved in the Vienna Circle
- According to Popper's critical rationalism, scientific statements have to be open for falsification

References:
Karl Popper: Logik der Forschung. 1935.

Students of engineering and natural sciences rarely attend dedicated lectures on the philosophy of science

Any implicit gained understanding of philosophy of science is most likely based on logical positivism, reductionism, and critical rationalism

Further Developments in the Philosophy of Science

- Later progress in the philosophy of science focus on social frameworks in which science take place
- Thomas Kuhn (1922 – 1996) was the first challenging a philosophy of science that omits the implications of human factors
  - He emphasizes the social-psychological dimension of science
  - Normal science serves an established research paradigm
  - After time, the limitations of a research paradigm will lead to the advent of a competing new search paradigm replacing the old one
- A good introduction into the contemporary philosophy of science has been written by Alan Chalmers

References:
Thomas S. Kuhn: The Structure of Scientific Revolution. 1962.
Alan F. Chalmers: What is this Thing Called Science. 3rd Edition, 1999.

As personal experience has shown, many engineers and natural scientist refuse Kuhn's view as a valid record of the philosophy of science

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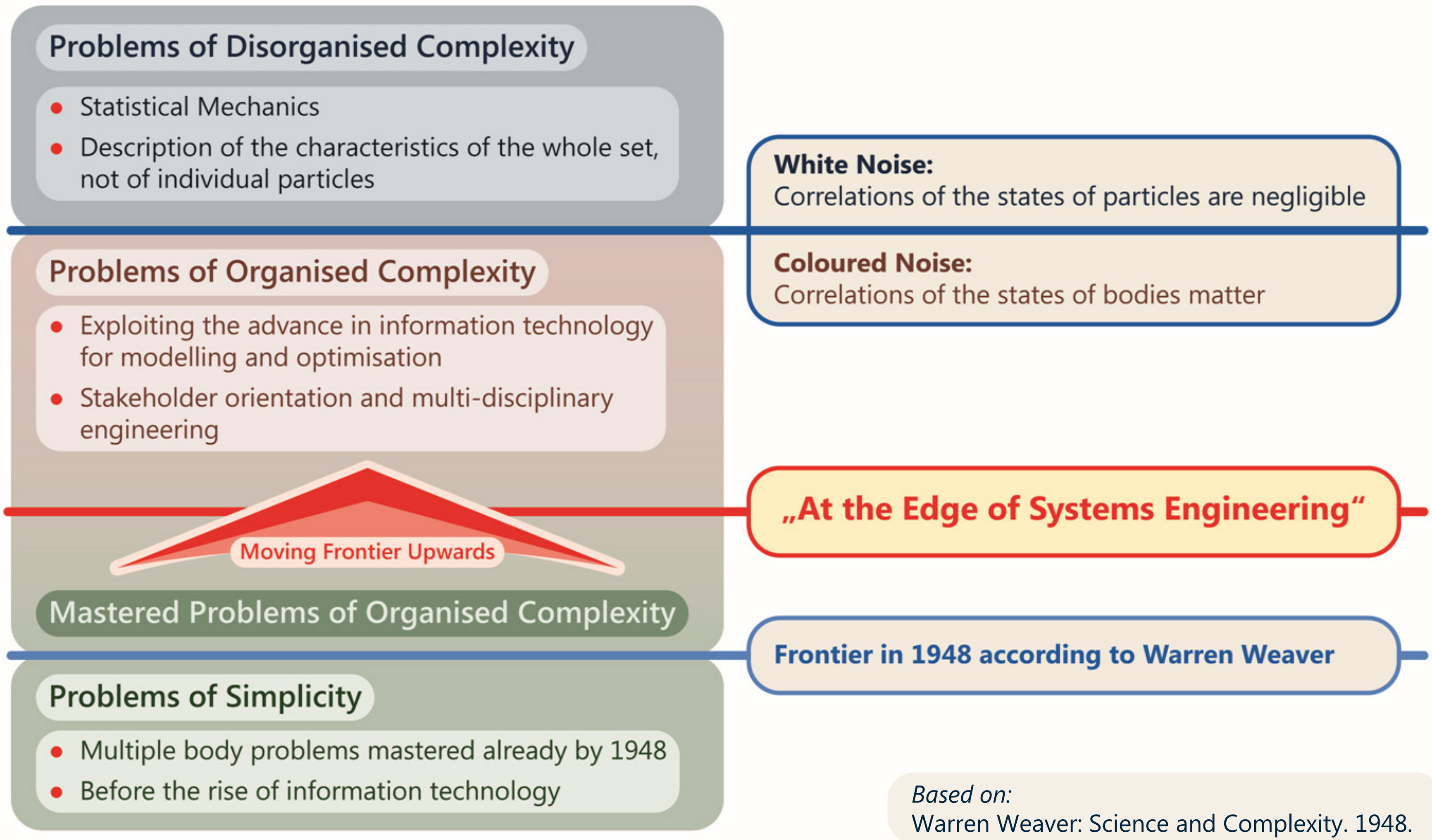
The Scope of Systems Engineering

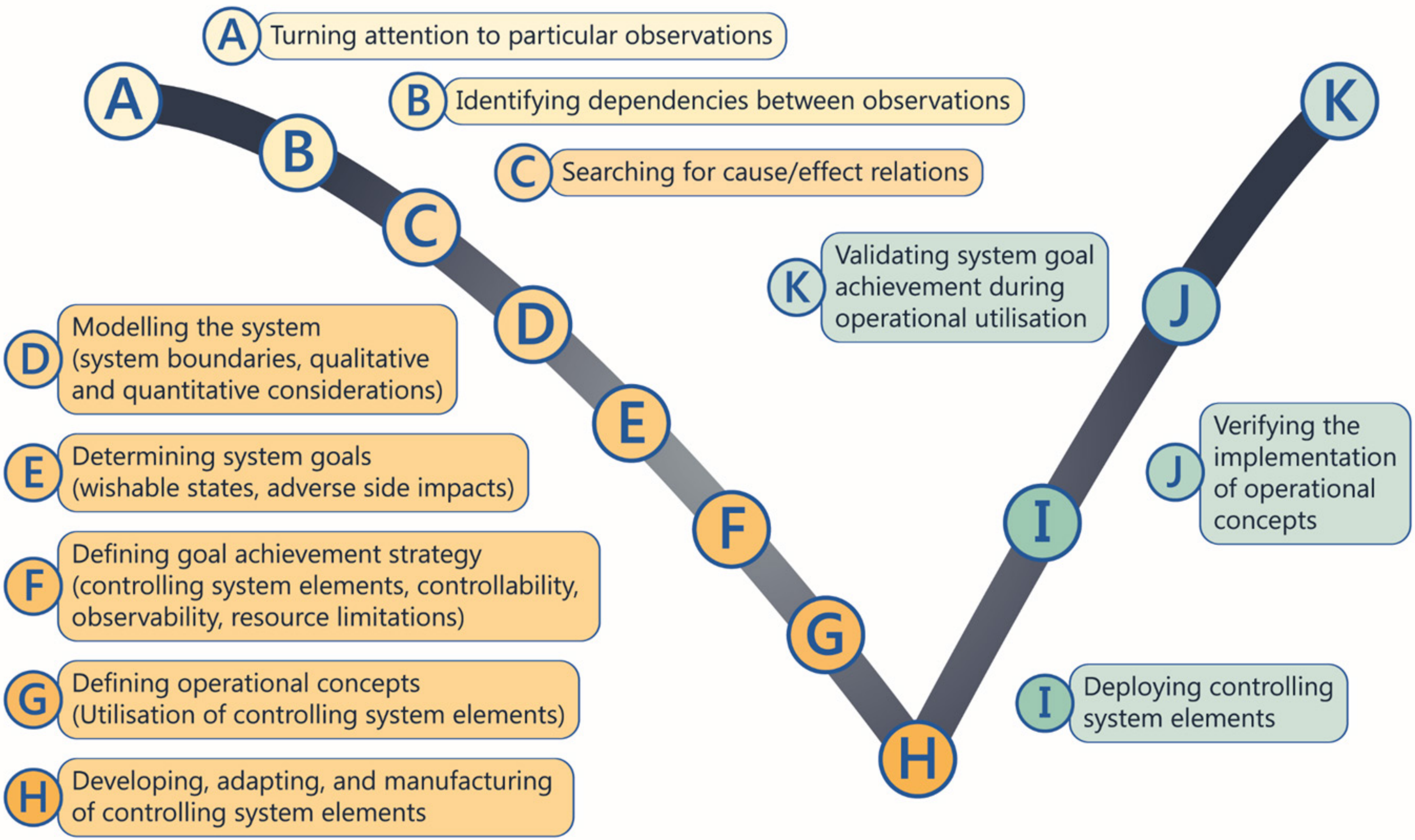
- At the Edge of Systems Engineering
- From Problem to System Solution
- The System Control Loop
- System Integrity
- The Dual Role of Systems Engineering
- Stakeholder Orientation and Multi-Disciplinarity as a Unique Human Capability

At the Edge of Systems Engineering

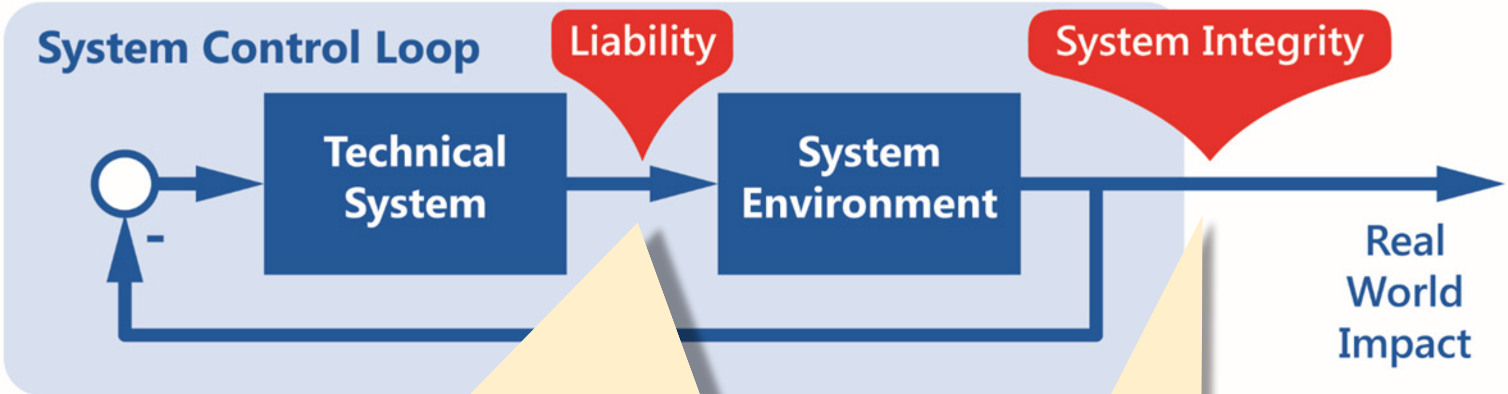


Based on:
Warren Weaver: Science and Complexity. 1948.

From Problem to System Solution



The System Control Loop



- Liability regarding safety, security etc. from the perspective of the producer of the Technical System
- In case of intended and foreseeable modes of operation, the Technical System shall neither generate personal or material damage nor pecuniary losses
- Failures in the Technical System shall do no damage to the System Environment

- System behavior complies with intended expectations
- Interpretation of the System Environment as an open system

System Integrity

Complexity due to Intended Globalization

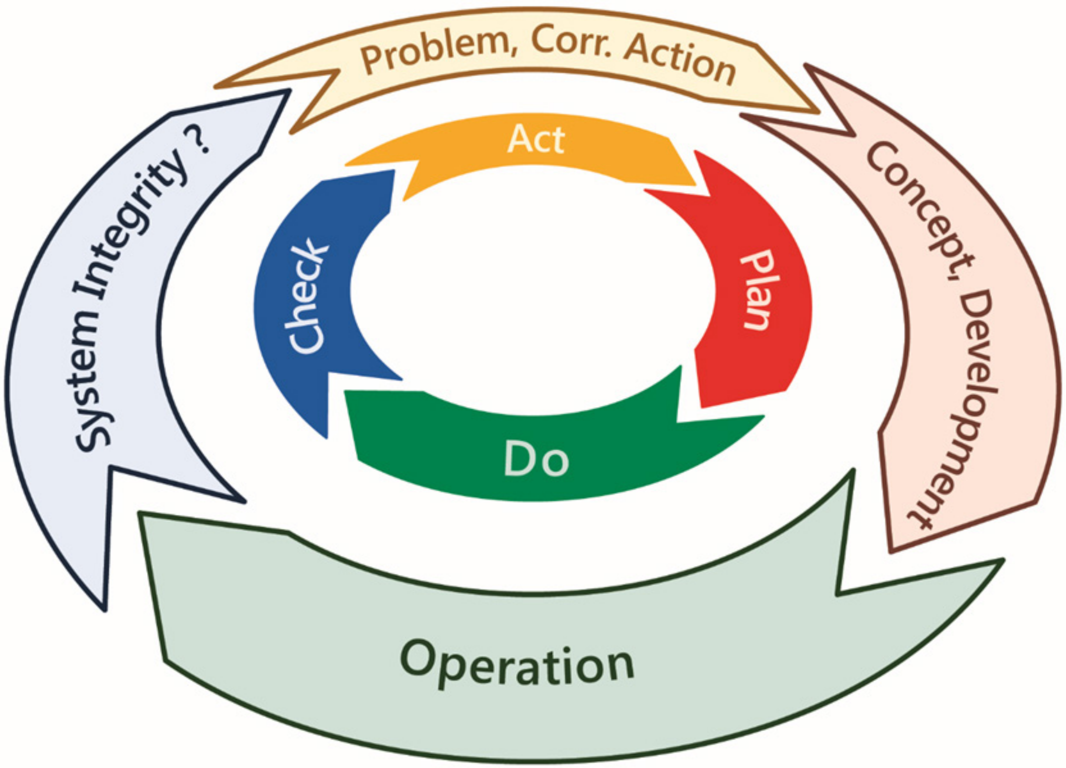
- Travel
- Trade
- Information Exchange
- Financial Transactions
- Global Environmental Impact

Complexity due to Resource Consumption at the Limits

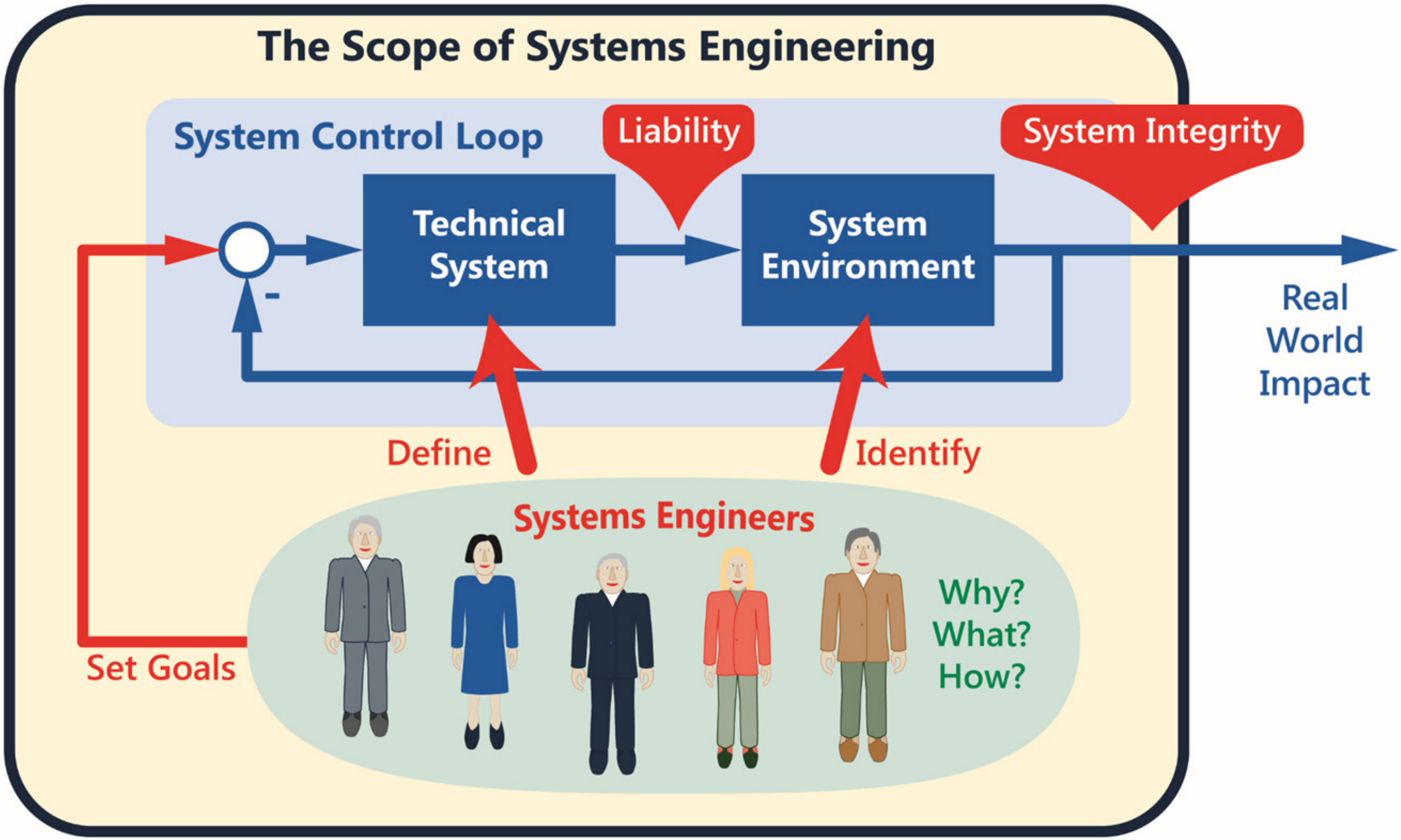
- Principle of small perturbations, if at all, only applicable in case of extending the system boundaries

System Integrity

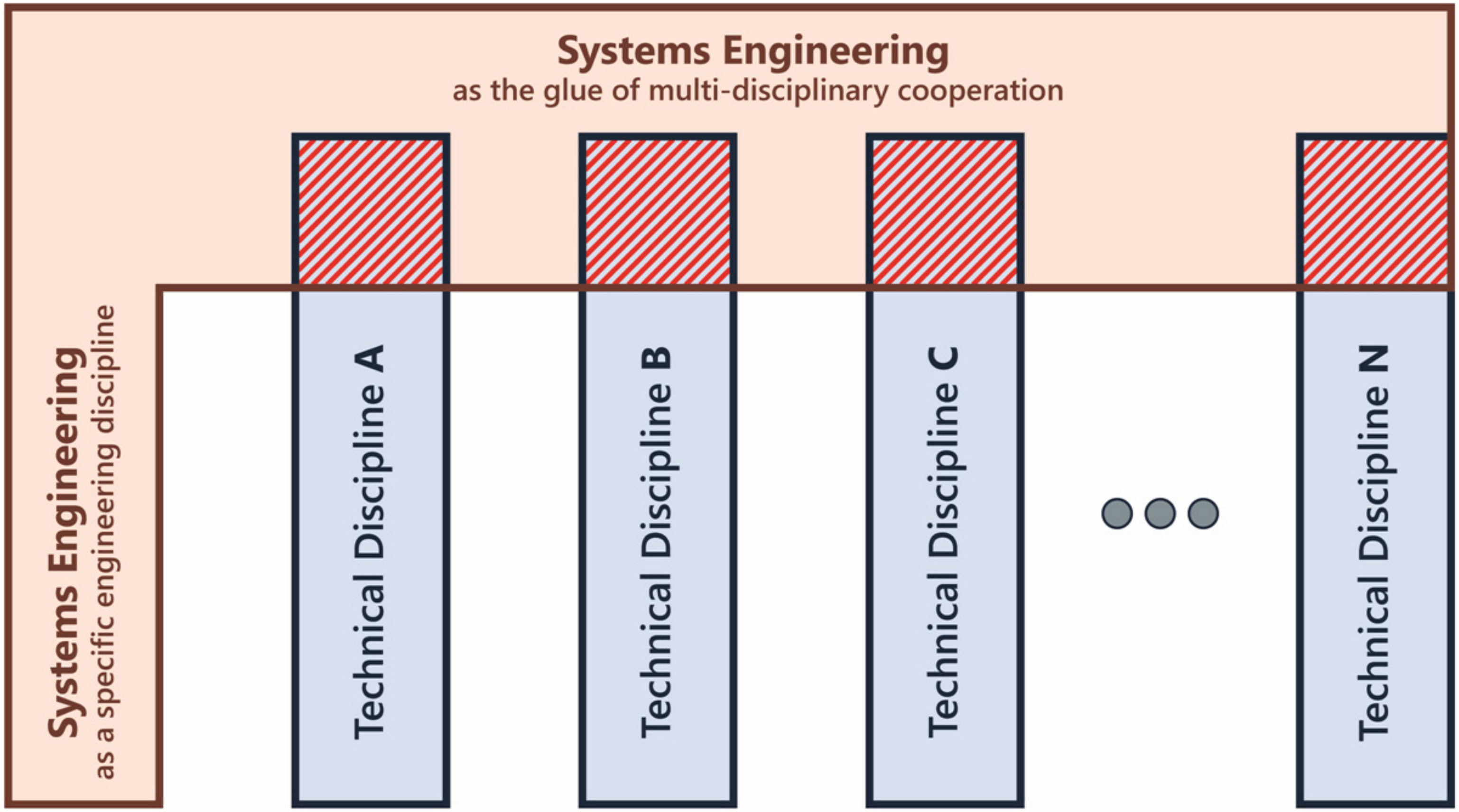
- System is sustainable
- System behavior complies with intended expectations under all environmental conditions



The Scope of Systems Engineering



The Dual Role of Systems Engineering



- ***Primarily demanded are engineers capable to present their discipline in the overall systems engineering endeavor***

Stakeholder Orientation and Multi-Disciplinarity as a Unique Human Capability

- Contemporary cognition research on animals and humans has disproved the claim of general difference of human cognitive capabilities to explain the dominance of humans on Earth

- Language and reasoning have been identified as the main difference
  - Communication between animals seems to be always imperative (warnings – hints – orders)
  - For two hunters discussing in which direction to follow a paw print, it is most reasonable for both to have something to eat at night

- Capabilities for multi-disciplinary engineering are evolutionary even more advanced
  - We are able to agree on common goals without knowing how other disciplines involved generate their contribution to the solution

References:
Frans de Waal: Are We Smart Enough to Know How Smart Animals are? 2016.
Michael Tomasello: A Natural History of Human Thinking. 2014.

Content

A Model of Semantic Memory

- Human Causation
- Neuronal Plasticity
- Semantic Memory
- Availability Heuristic
- Conscious Perception
- Narration Theory

Human Causation

- David Hume (1711 – 1776) established a theory on human causation that has widely be confirmed by modern science
  - (1) The cause and effect must be contiguous in space and time.
  - (2) The cause must be prior to the effect.
  - (3) There must be a constant union betwixt the cause and effect.
- Human Causation is compatible with information theory
  - The effect does not change the cause like information flows unidirectionally from a source to one or multiple sinks
- Causality in scientific field theories is different from human causation
  - Objects in the field are mutual influenced by the field forces
  - Feedback theory enables an expression of causality by information theory

References:
David Hume: A Treatise of the Human Nature. 1739.
Don Garrett: Hume. The Oxford Handbook of Causation. 2009.

Neuronal Plasticity

- The brain is neither a digital computer, nor follows it the concepts of John von Neumann
- In the nervous system, the structure is the algorithm and the memory at once
- To a wide extent the structure of the brain is determined by genetic and epigenetic factors
- Plasticity within the brain is enabled by
  - generating new neurons and synaptic connections
  - strengthening and rebuilding synaptic connections as revealed by Eric Kandel's research

References:
Eric Kandel: In Search of Memory – The Emergence of a New Science of the Mind. 2006.

Semantic Memory

- All perceptions are transiently stored in Short-Term Memory, and Working Memory
- Permanent storage in the cerebral cortex is divided into
  - Historic Memory
  - Semantic Memory
- Both, Historic Memory and Semantic Memory, are dynamically changing
- Real-time behavior is achieved by augmenting current perceptions by the patterns stored in the Semantic Memory

References:
E. Bruce Goldstein: Sensation and Perception. International Edition, 2009.
E. Bruce Goldstein: Cognitive Psychology – Connecting Mind, Research and Everyday Experience. 2015.

Availability Heuristics

- Amon Tversky and Daniel Kahnemann derived a number of heuristics about human judgement and behavior by experimental psychology
- The Availability Heuristic comprises the finding that information priming has an impact on how perceptions are observed
- If the primed information and the presented information are related closely and compliant, the later information is more easily remembered and is processed faster than in case of independent or conflicting information

References:
Daniel Kahnemann: Thinking, Fast and Slow. 2011.

Conscious Perception

- EEG and brain imaging technology have been supportive to translate conscious perception into neuronal activity
- Basic stages of perception are running in parallel
- Conscious perception is characterized by
  - Synchronized activity of wide areas of the cerebral cortex
  - Some areas of the cerebral cortex are activated while other areas are inhibited
- Conscious perception is always one third of a second behind the fact

References:

Stanislas Dehaene: Consciousness and the Brain – Deciphering How the Brain Codes Our Thoughts. 2014.

Narration Theory

- Narratives follow a pattern: „Then …, and then …, and then…"
  - Regarding the "and then", causal dependencies are better remembered than time sequences
  - Lengthy side stories reduce communication efficiency
- Note, the semantic memory is organized as a network of neurons
  - Many stories may be told traversing this network
  - Leaving some information out may strengthen a narrative, but may drop essential information
(Example: Deficient considerations on system interface engineering)
  - Too many side stories clutter essential statements
(Example: System requirements for expressing commitments to be verified)

References:
Yuri M. Lotman: Universe of the Mind – A Semiotic Theory of Culture. 1990.
Albrecht Koschorke: Wahrheit und Erfindung – Grundzüge einer allgemeinen Erzähltheorie. 2012.

Content

Three Essential Systems Engineering Narratives

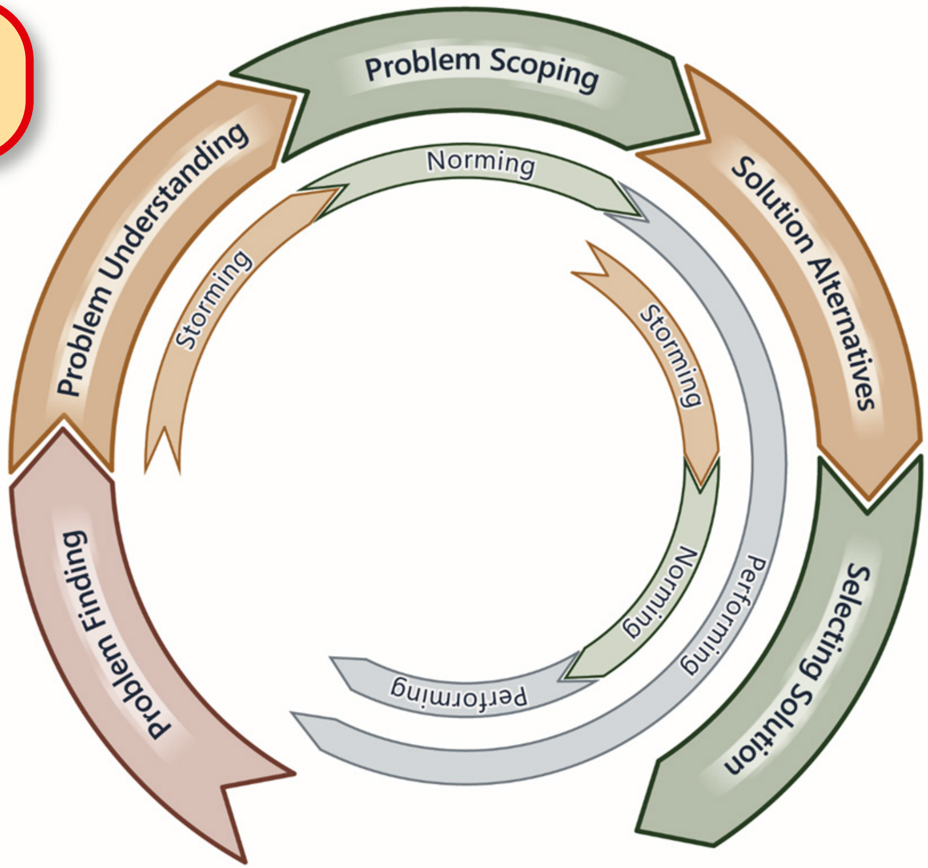
- Demands on the Content of a Basic Narrative
- The Problem Processing Cycle
- The Systems Engineering Value Stream
- The System Life Cycle

Demands on the Content of a Basic Narrative

- Self-contained
- Convincing causation
- Limited number of side stories not cluttering the main narrative
- Free of contradictions
- Connected to existing knowledge and experience
- Extendable to allow integration with more detailed knowledge
- Open for the integration of further experience

The Problem Processing Cycle

The Individual in an Engineering Team



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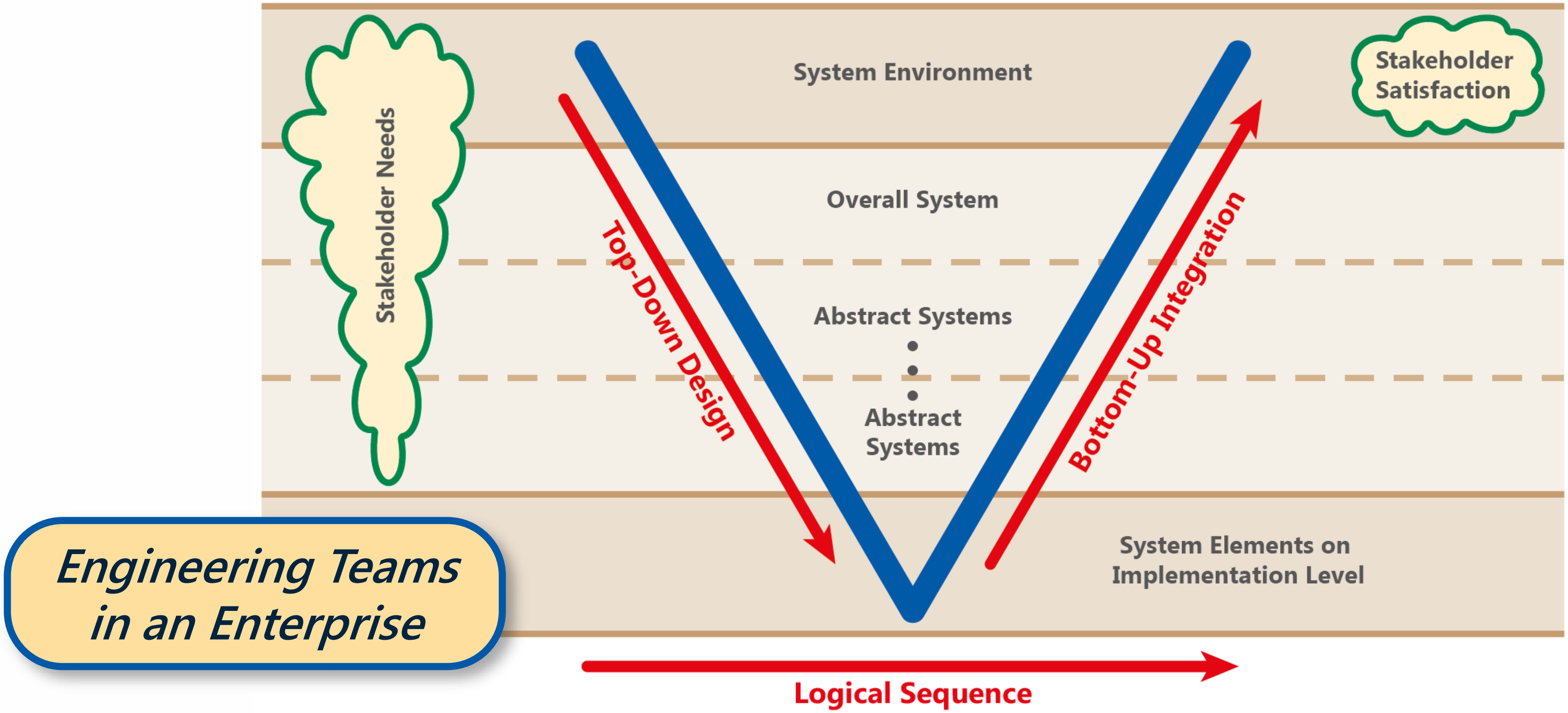
The Systems Engineering Value Stream



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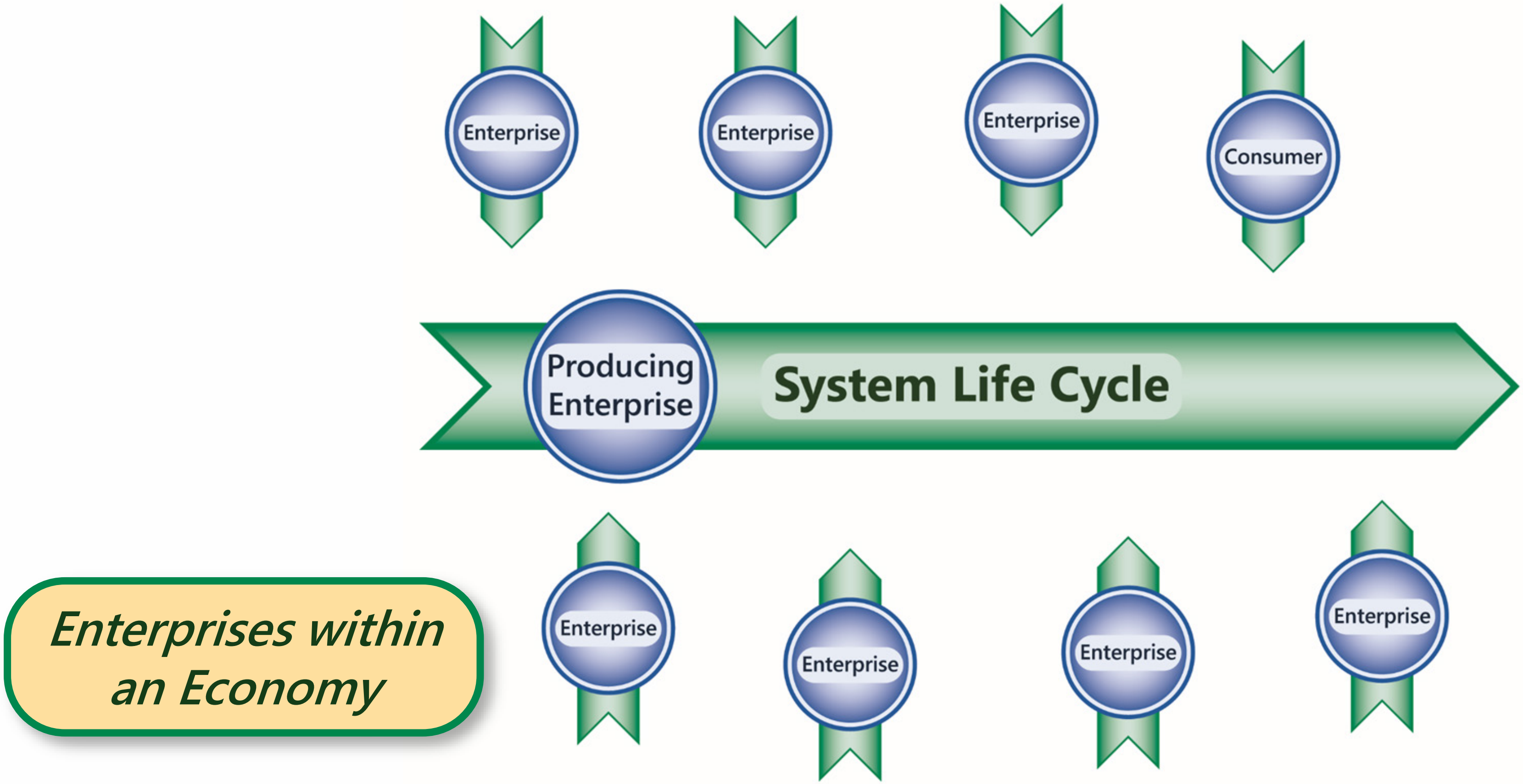
Dieter Scheithauer: System Value Stream Modelling. EMEASEC 2014
Dieter Scheithauer: System Interface Engineering. IS 2015.

The System Life Cycle



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Dieter Scheithauer: The Role of Systems Engineering in Business Planning. IS 2014.

Dieter Scheithauer: System Interfaces and System Interoperability in a System-of-Systems Context. 2015.

Thank You

for your attention

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