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Systems Engineering (SySe)
Chapter 1 – Systems Engineering & Systems

Prof. Dr. Silke Lechner-Greite

Content

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All about Systems Engineering

1. Why do we need Systems Engineering?
2. What is Systems Engineering?
3. When do we use Systems Engineering?
4. Who is the Systems Engineer?
5. What are important components in Systems Engineering?

All about Systems

1. Systems, elements, relations, subsystems
2. System boundary and environment
3. Subsystems
4. Systems of systems
5. Complicated vs. complex systems
6. (Complex) Technical systems

Why do we need systems engineering?

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A question to all:

Why do we need Systems Engineering?

Discuss with your neighbour (~ 3 mins)

Why do we need Systems Engineering?

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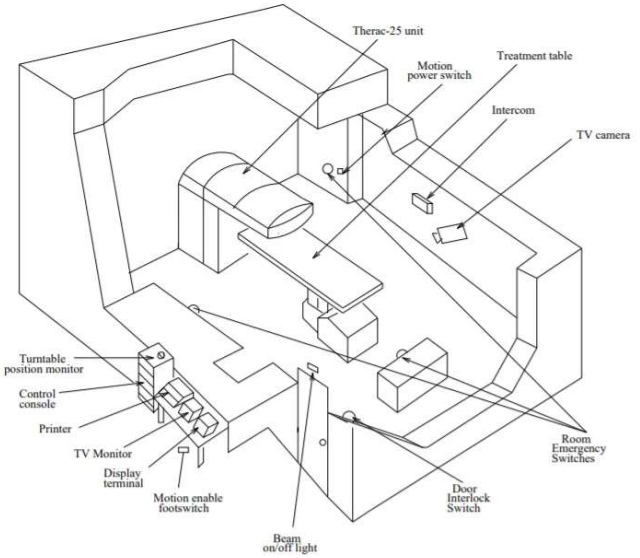
- **Therac-25** was an electron linear accelerator. As therapeutic radiation, especially for cancer therapy, either the electron beam directly, or the X-ray radiation of the energy 25 MeV generated by an intermediate target made of tungsten (Wolfram) could be used. In direct mode, a much lower strength of the electron beam was set than in X-ray mode.

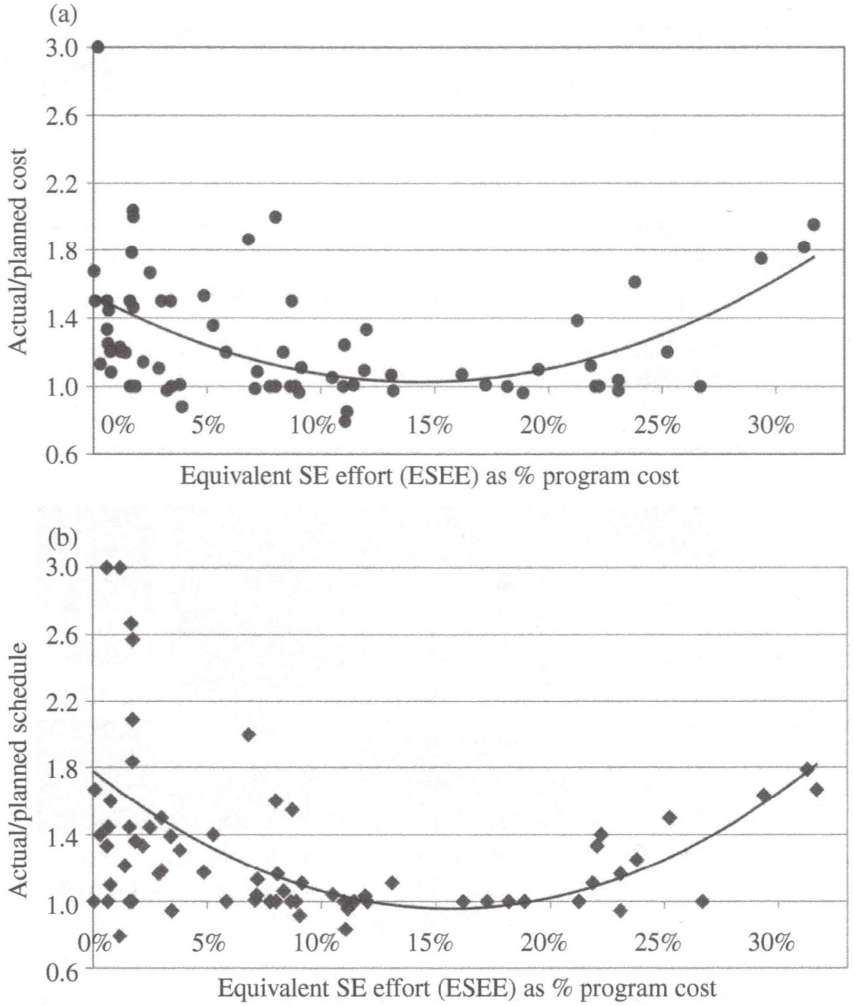
- The Therac-25 led to severe over radiation in several accidents between 1985 and 1987. At least six patients were injured, some died.

- Reasons:
  - Software bug: programming errors led to extremely high radiation doses.
  - Lack of hardware security mechanisms: Previous models had hardware safeguards that were removed on the Therac-25.
  - Inadequate testing procedures: The software has not been sufficiently tested.
  - Lack of error analysis: Problems were not detected and rectified in time.
- Consequences:
  - The case led to stricter regulations and standards for medical device development and testing.



(Source: https://alerner1st.medium.com/worlds-worst-software-bugs-the-therac-25-disaster-36236c126382)

Why do we need Systems Engineering?



Graph taken from (1): Cost (a) and schedule (b) overrun correlated with Software Engineering efforts.

(1) INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

- Complex Technical Systems need a handle on change management by reducing the risks that come with system modifications → keep costs down → keep project in time
- These graphs are taken from [1], where a study looked at how the use of SE has affected planned costs and schedules.
- The graph shows normalised data to make projects comparable: programme size divided by cost
- The graph shows that the ideal SE effort is 14% of the total programme cost.
- The study also found that the current SE effort is 7% of the total programme cost.
- **Yes --- cost and schedule are correlated with Systems Engineering efforts**

Why do we need Systems Engineering?

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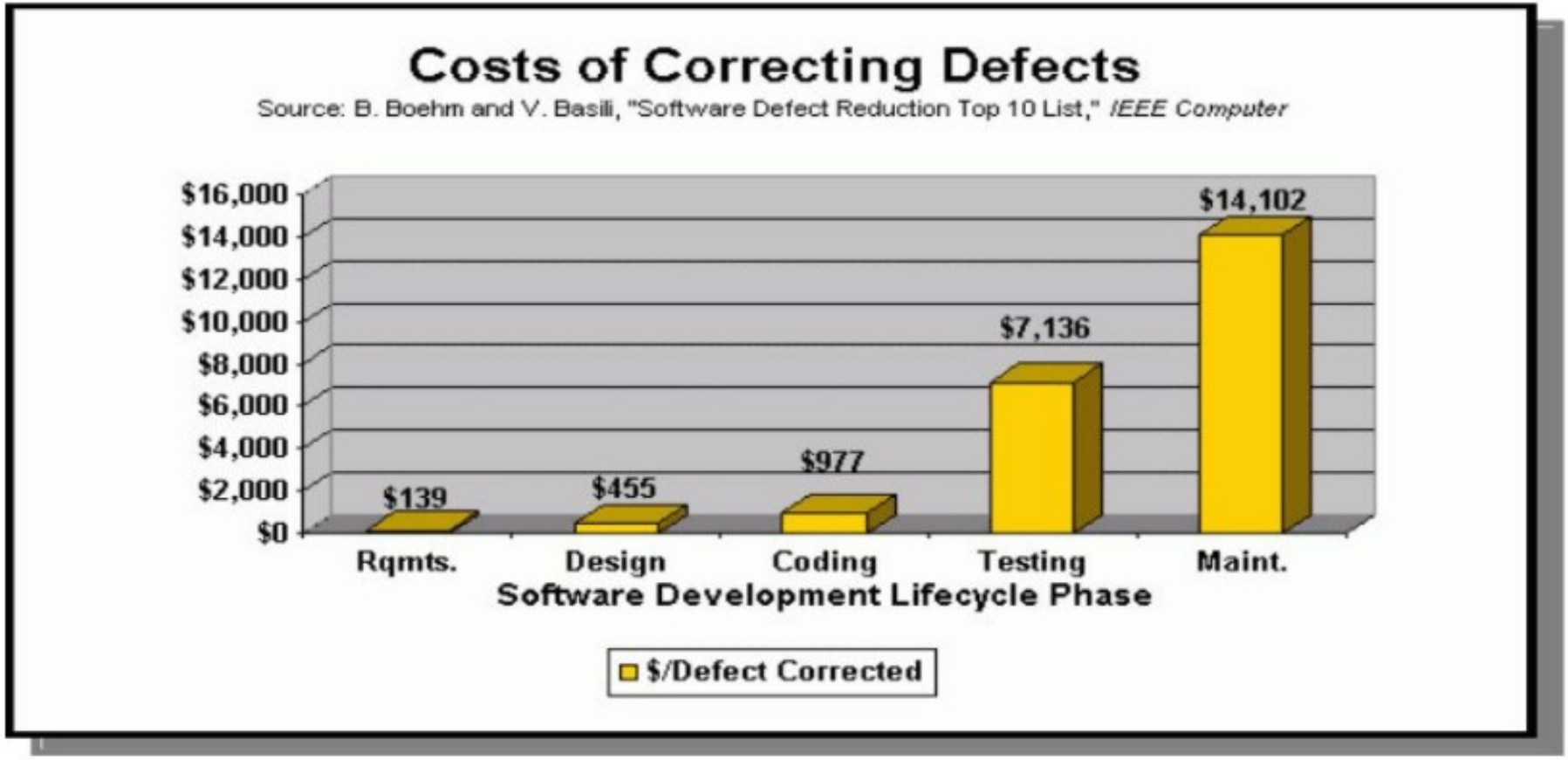
- The earlier you find a software defect, the lower the cost to repair.



(Original Source: B. Boehm and V. Basili, Software Defect Reduction Top 10 List, IEEE Computer, IEEE Computer Society, Vol. 34, No. 1, January 2001, pp. 135-137; https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=962984

Graph taken from here: https://slcontrols.com/justify-early-extra-investment-reduce-late-budget-overruns/)

Why do we need Systems Engineering?

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- Simply put, one can't afford not to use systems engineering and it's hard to justify!

- There are many good reasons, i.e.
  - Reducing **complexity**
  - Reduce **time**
  - Reducing **cost**
  - Integrate new components seamlessly
  - Improved **risk** management
  - Efficient use of **resources**
  - Enhance system **reliability**
  - Facilitate system **scalability** and adaptability
  - Ensure **compliance** (i.e. standards, regulatory, etc.)
  - Foster **interdisciplinary** collaboration between engineering teams
  - **Lifecycle** management
  - Increase **customer satisfaction**
  - Encourage **innovation**
  - …

What is Systems Engineering for you?

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A question to all:

What is Systems Engineering for you?

Discuss with your neighbour (~ 3 mins)

What is Systems Engineering?

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Interdisciplinary approach to realize successful systems → expertise of various disciplines coordinated by systems engineer

Detect/Define the interrelations of system elements

Identify and define system requirements to achieve a system that meets the users needs

Apply iterative approaches to support discovery, learning, continuous improvement

Apply strategic approaches and think based on “Systems Thinking”

Make “good” or “right” decisions in a timely manner

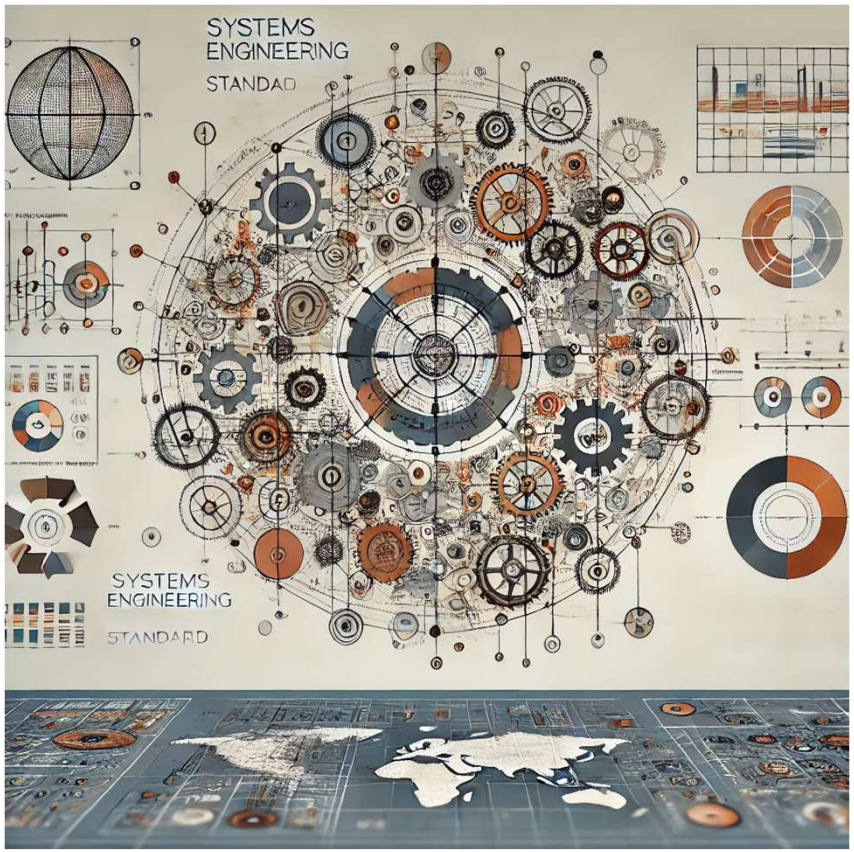
From concept to production to operation

What is Systems Engineering?

- Defined in international standard ISO/IEC/IEEE 15288 (first in 2002); current status from 2023: https://www.iso.org/standard/81702.html

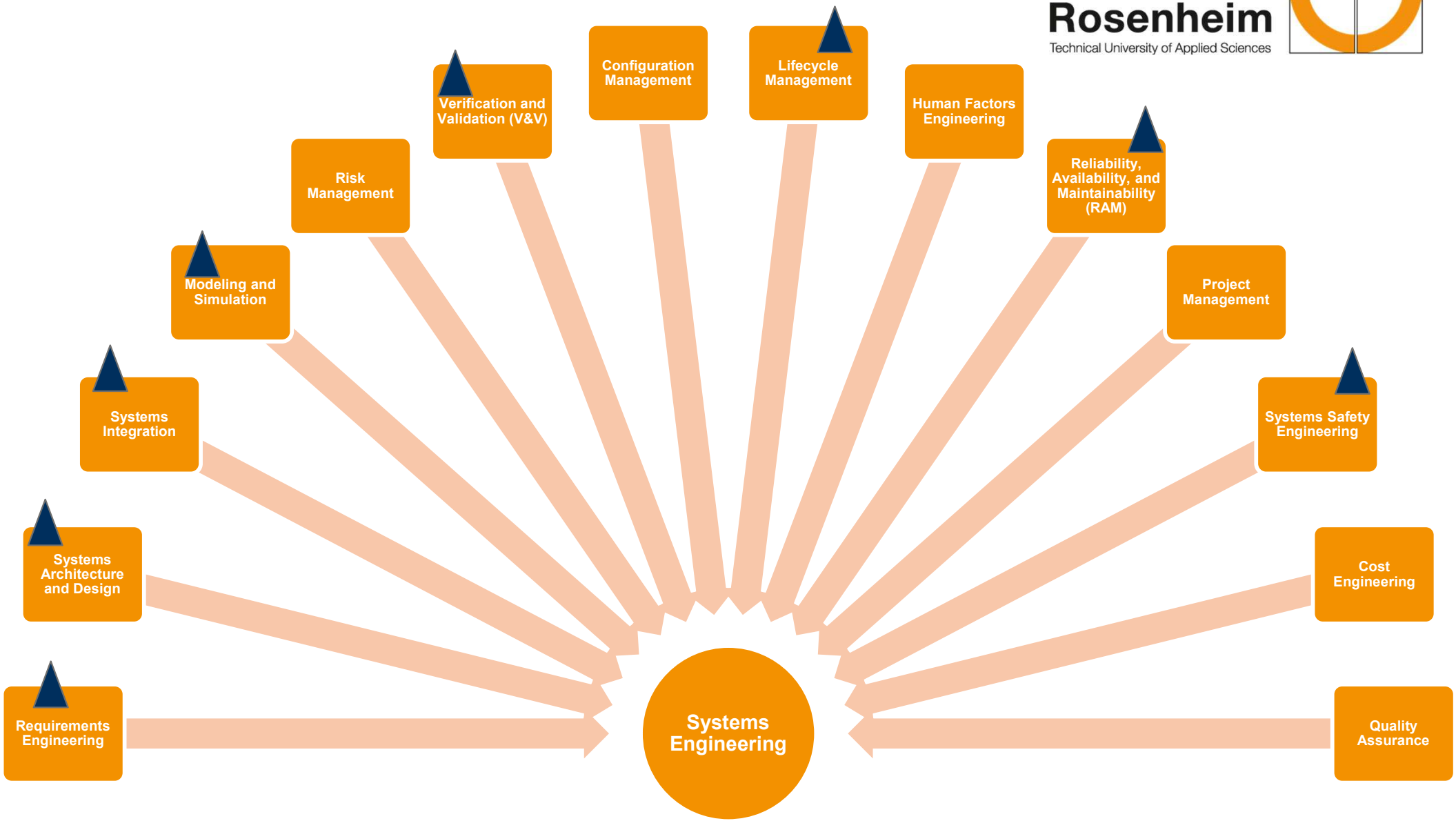
- Defined as: systems engineering – " … *transdisciplinary and integrative approach to enable the successful realization, use, and retirement … of engineered systems … using systems principles and concepts and scientific, technological and management methods* … "

➢ Support the development of complex systems
➢ Convert a need into a suitable solution
➢ Find the right design and identify the right processes/techniques/methodologies to manage complexity.
➢ Look at the big picture "Vogel- und Froschperspektive"
➢ Systems Engineering to guide the engineering



(Source: OpenAI. (2024). Systems engineering standard representation [Digitales Bild]. Generiert durch ChatGPT.

System Engineering Disciplines



Overlap of disciplines possible.

It is a combination between managerial and engineering practices.

When do we use Systems Engineering?

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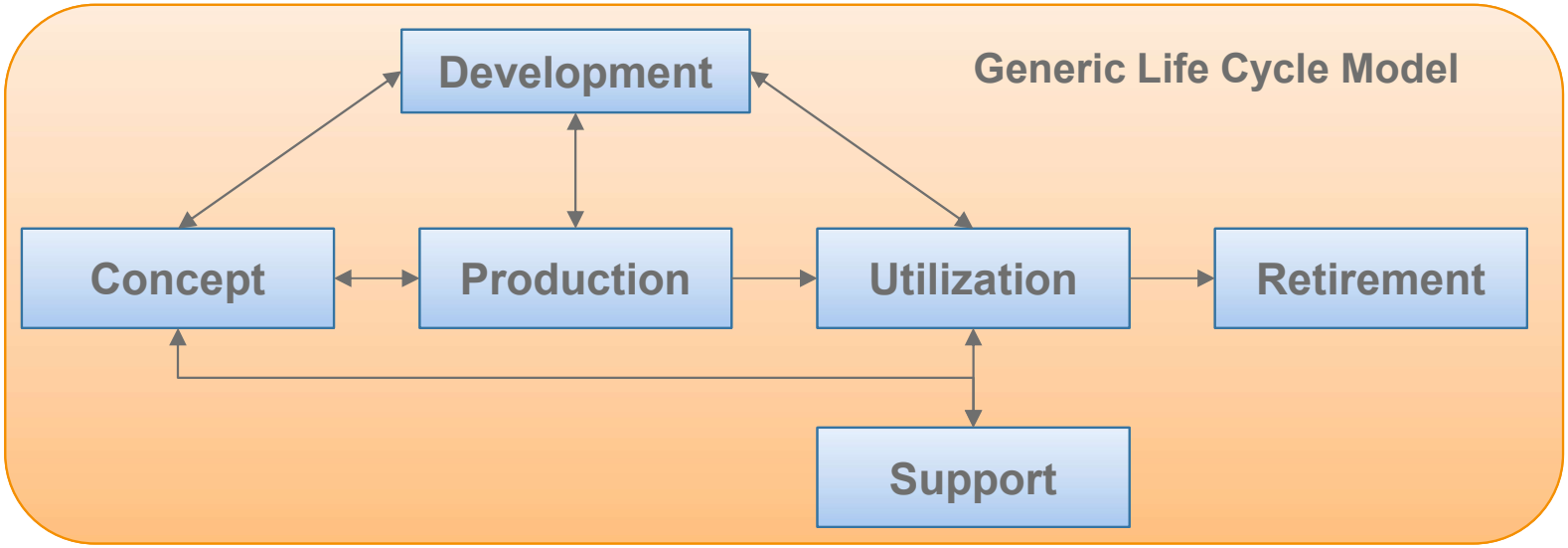
A question to all:

When do we use Systems Engineering?

Discuss with your neighbour (~ 3 mins)

When do we use Systems Engineering?



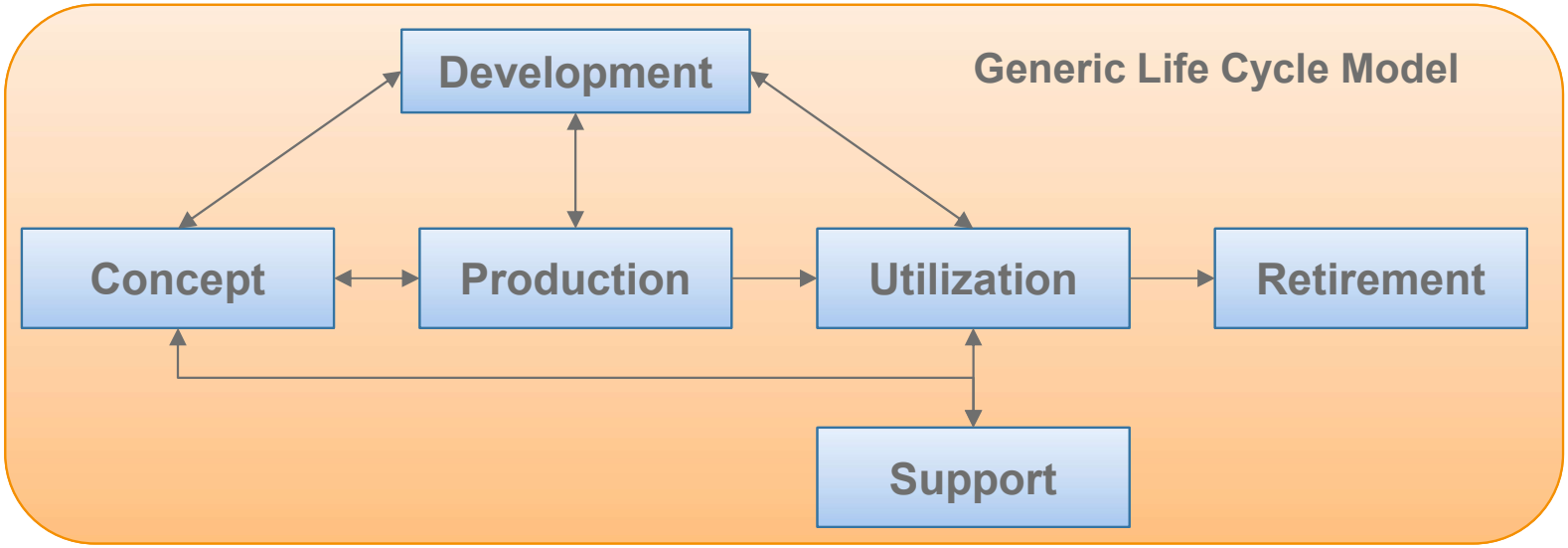
“ … Life cycles vary according to the nature, purpose, use and prevailing circumstances of the system …” (1, also graph)

“ … Life cycles provide a framework for meeting the stakeholder/customer needs and to keep the project in time. …” (1)

→ **Efficient methods**
→ **Life cycle stages**
→ **Decision gates** to decide readiness of life cycle stages (see next slide)

(1) INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

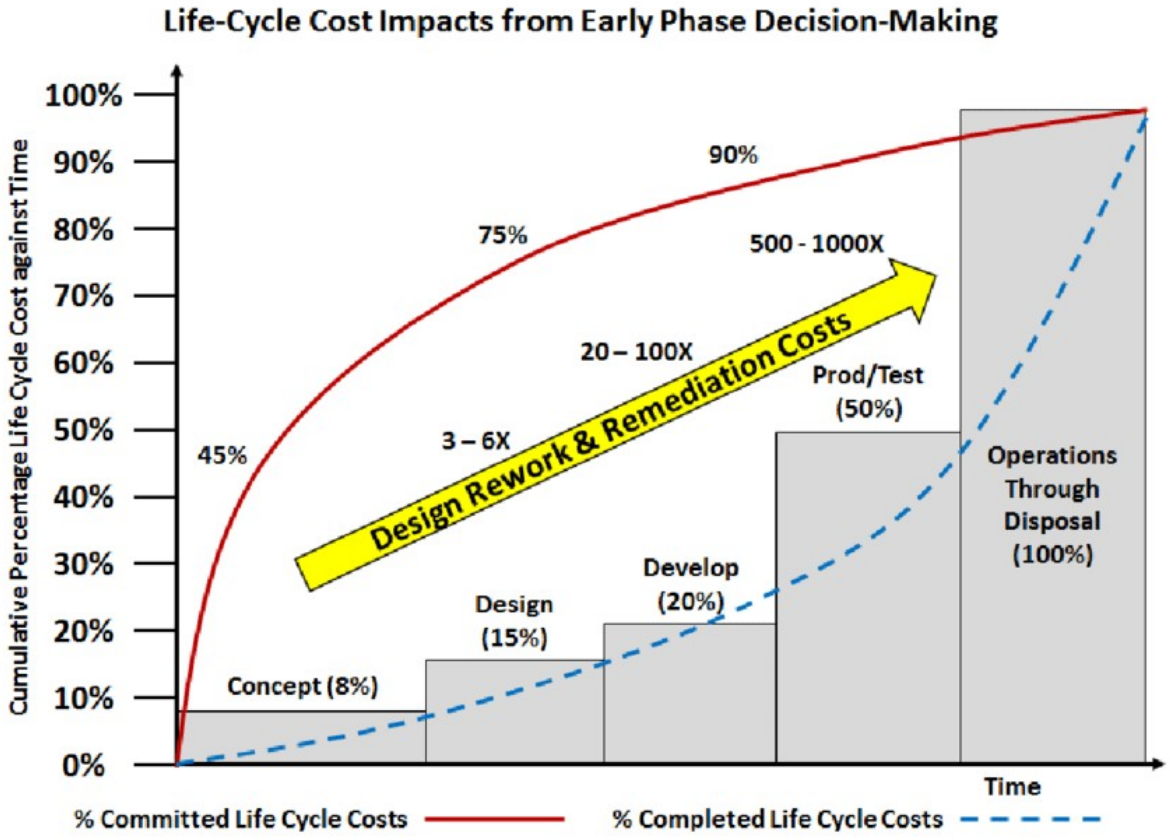
When do we use Systems Engineering?



- Systems Engineering is important in all life cycle stages!
- Why? For example …
  - Needs can change during production phase
  - Needs can change during operation
  - System technology evolves
  - Data from utilization phase can give valuable insights into new system versions (performance analysis, interface analysis, management, etc.)
- Three aspects:
  - Business case ↔ Funding ↔ Technology
  - System Engineer: helps building a technology that is aligned with business case & funding
  - System integrity: all three aspects are weighted equally important

(1) INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

When do we use Systems Engineering?



(1) Shallcross, Nicholas. (2021). Quantitative Set-Based Design for Complex System Development. Original from INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

- Committed life cycle cost against time
- Illustrates the necessity and impact in making early decision without the benefit of good information and analysis.
- Increased effort in concept exploration to reduce the risk of hasty commitments without adequate study.

Who is the Systems Engineer?

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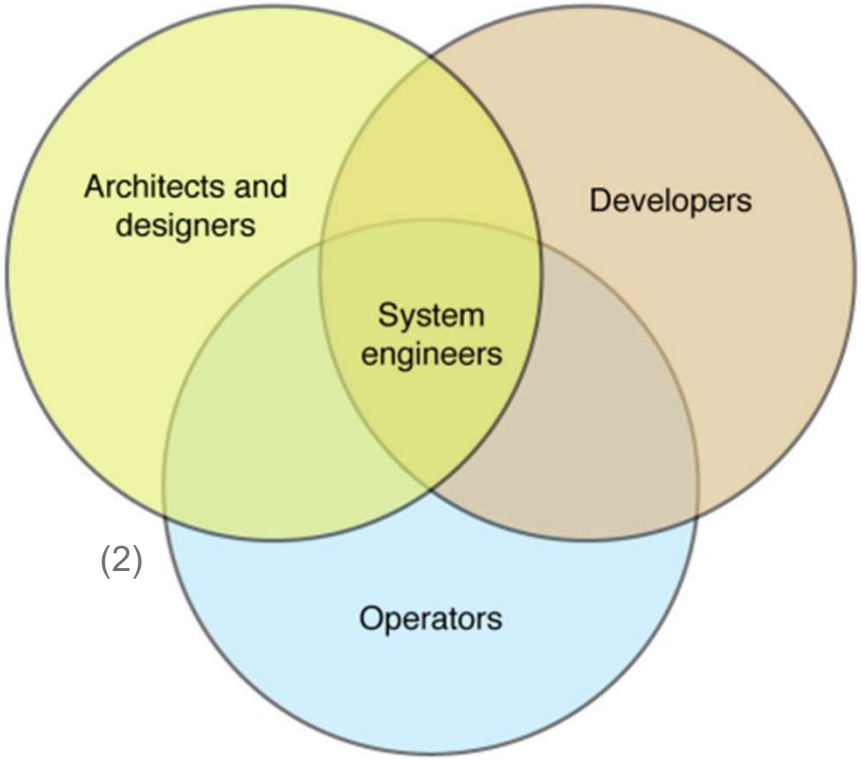
A question to all:

Who is the Systems Engineer?

Discuss with your neighbour (~ 3 mins)

Who is the Systems Engineer?



(2)

- The systems engineer is described by his roles and responsibilities.
- " … Systems engineers are concerned with operations, too, but are more likely to…emphasize the machines than the procedures by which the machines are used. Furthermore, [SE's] are more likely to be engaged in the design of systems yet to be, rather than the operation of systems in being … " (1)

Figure 1. The Scope of Systems Engineering. Systems engineers often focus on one lifecycle phase like architecture and design versus development or operations, but good systems engineers have knowledge of and experience in all phases.

Sources:
(1) Chambers, What is a systems engineer? IEEE Transactions on Systems, Man, and Cybernetics (Volume: SMC-15, Issue: 4, July-Aug. 1985) https://ieeexplore.ieee.org/document/6313417
(2) Graph: Ryschkewitsch et al., The Art and Science of Systems Engineering; 2009; https://appel.nasa.gov/wp-content/uploads/2013/05/Art_and_Sci_of_SE_LONG_1_20_09.pdf

Who is the Systems Engineer?

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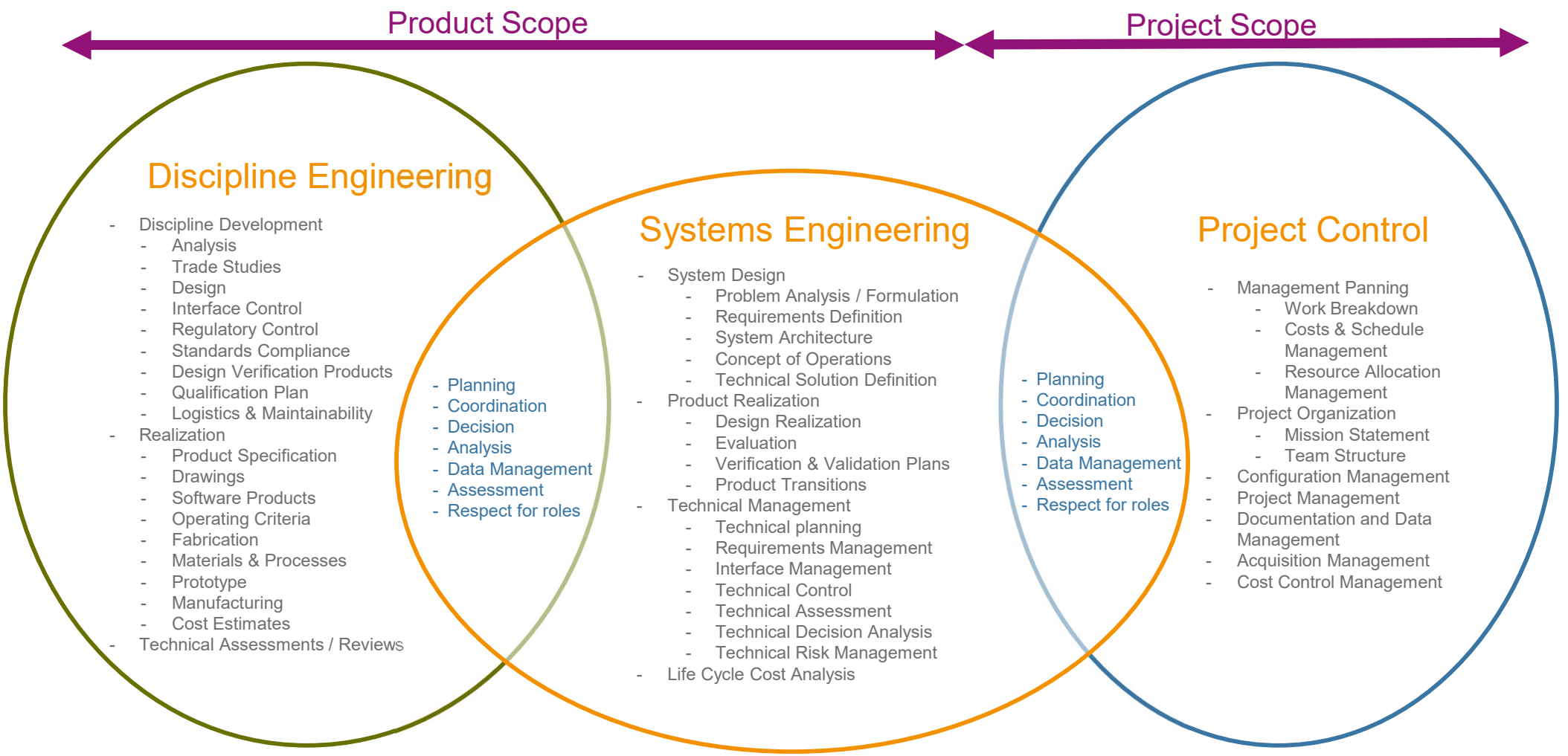

Responsibilities of Systems Engineer, Project Manager and Engineering

Source: Graph taken from Garcia et al., Systems Engineering Essentials; 2011, Online Presentation; https://ntrs.nasa.gov/api/citations/20110014955/downloads/20110014955.pdf

A Good Systems Engineer …

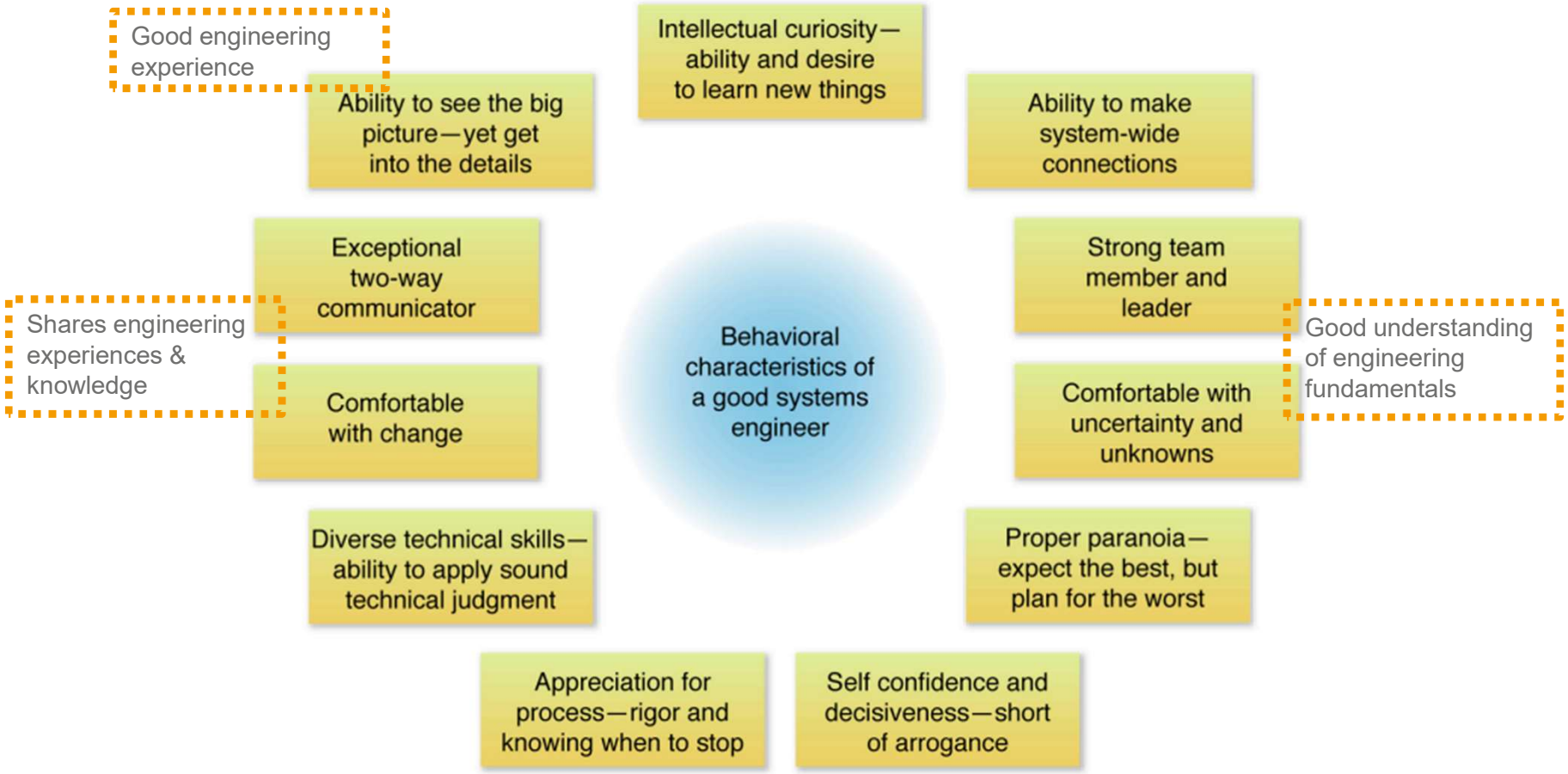

Figure 2. Characteristics of a Good Systems Engineer. The characteristics are shown in decreasing priority from top to bottom. Some of them are innate, whereas others can be learned and honed.

Source: Ryschkewitsch et al., The Art and Science of Systems Engineering; 2009; https://appel.nasa.gov/wp-content/uploads/2013/05/Art_and_Sci_of_SE_LONG_1_20_09.pdf

What are important components in Systems Engineering?

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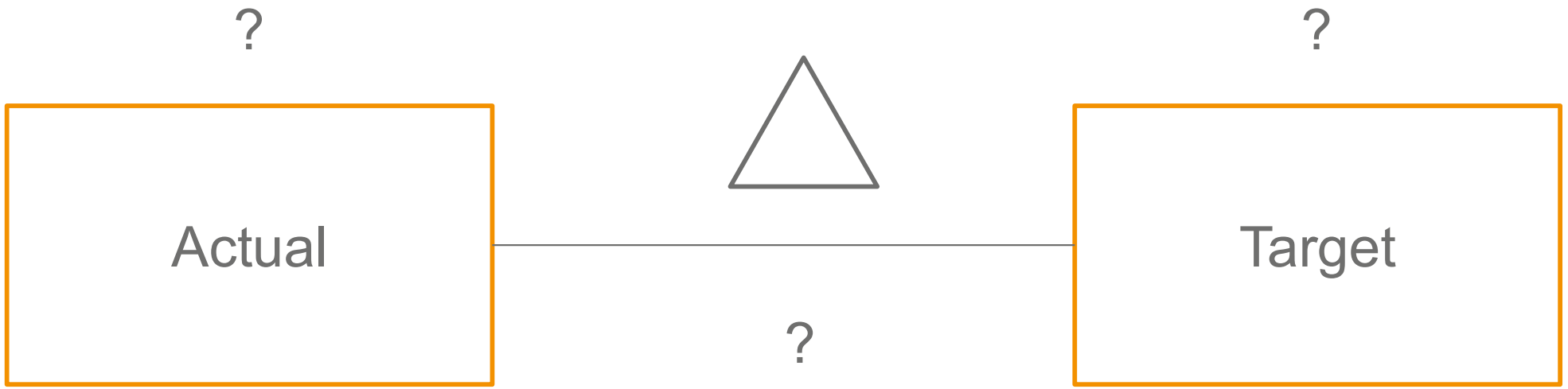
A question to all:

What are important components in Systems Engineering?

Discuss with your neighbour (~ 3 mins)

What are important components in Systems Engineering?

- Problem as difference between ACTUAL and TARGET



“ … if you want to solve a problem, there are usually many factors that determine it …”

(1) From Haberfellner et al., Systems Engineering Grundlagen und Anwendung, orell füssli 2018 (14. Auflage)

What are important components in Systems Engineering?

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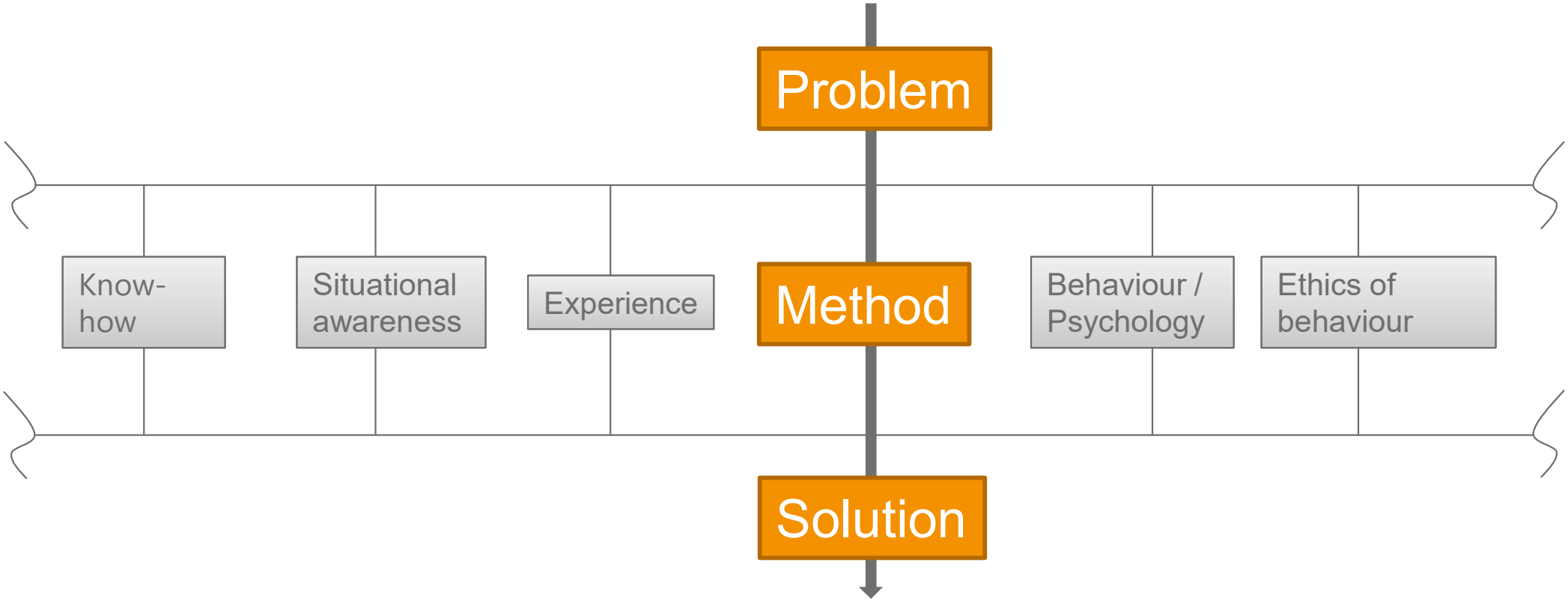
- System Engineering as a methodological component in problem solving



But:

" … Systems Engineering as a "Bindestrich-Disziplin" of several disciplines…"

(1) From Haberfellner et al., Systems Engineering Grundlagen und Anwendung, orell füssli 2018 (14. Auflage)

What are important components in Systems Engineering?

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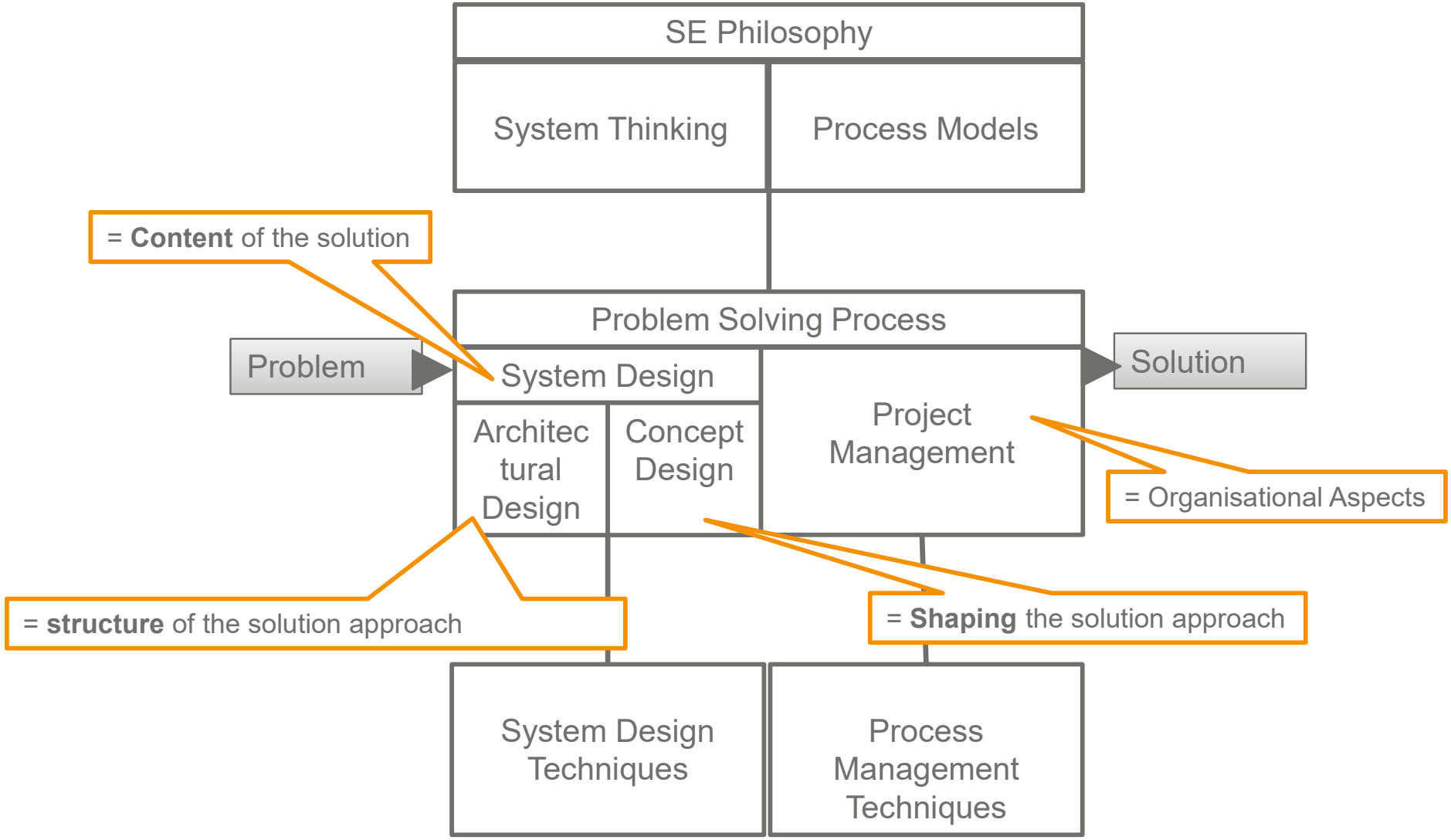
- System Engineering Concept



(1) From Haberfellner et al., Systems Engineering Grundlagen und Anwendung, orell füssli 2018 (14. Auflage)

Systems Engineering V-Model

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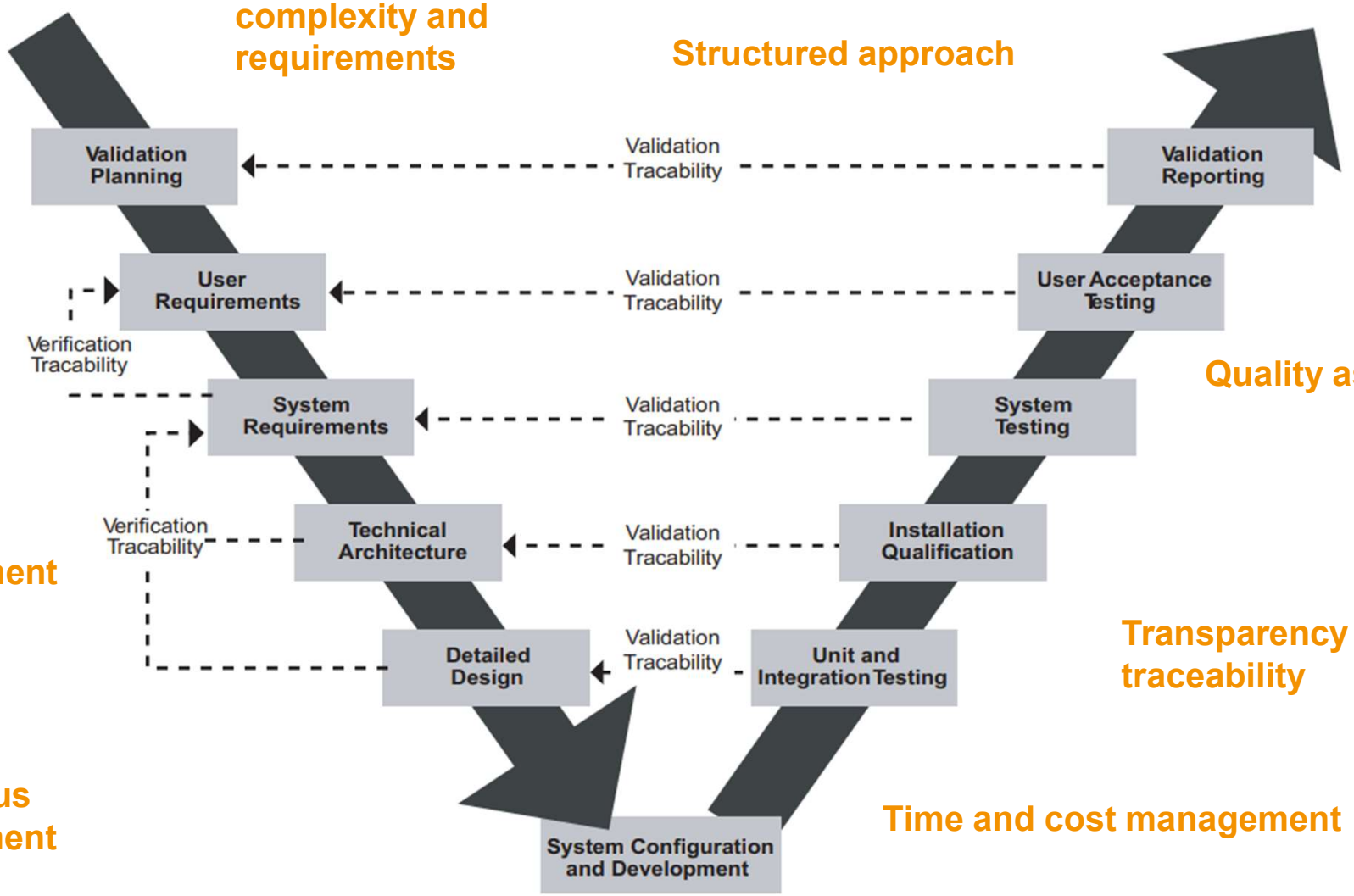
Adaptation to complexity and requirements

Structured approach



Quality assurance

Risk and change management

Transparency and traceability

Continuous improvement

Time and cost management

(1) Turner et al., Towards Agile Systems Engineering Processes; CROSSTALK The Journal of Defense Software Engineering; 2007

Content

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All about Systems Engineering

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All about Systems

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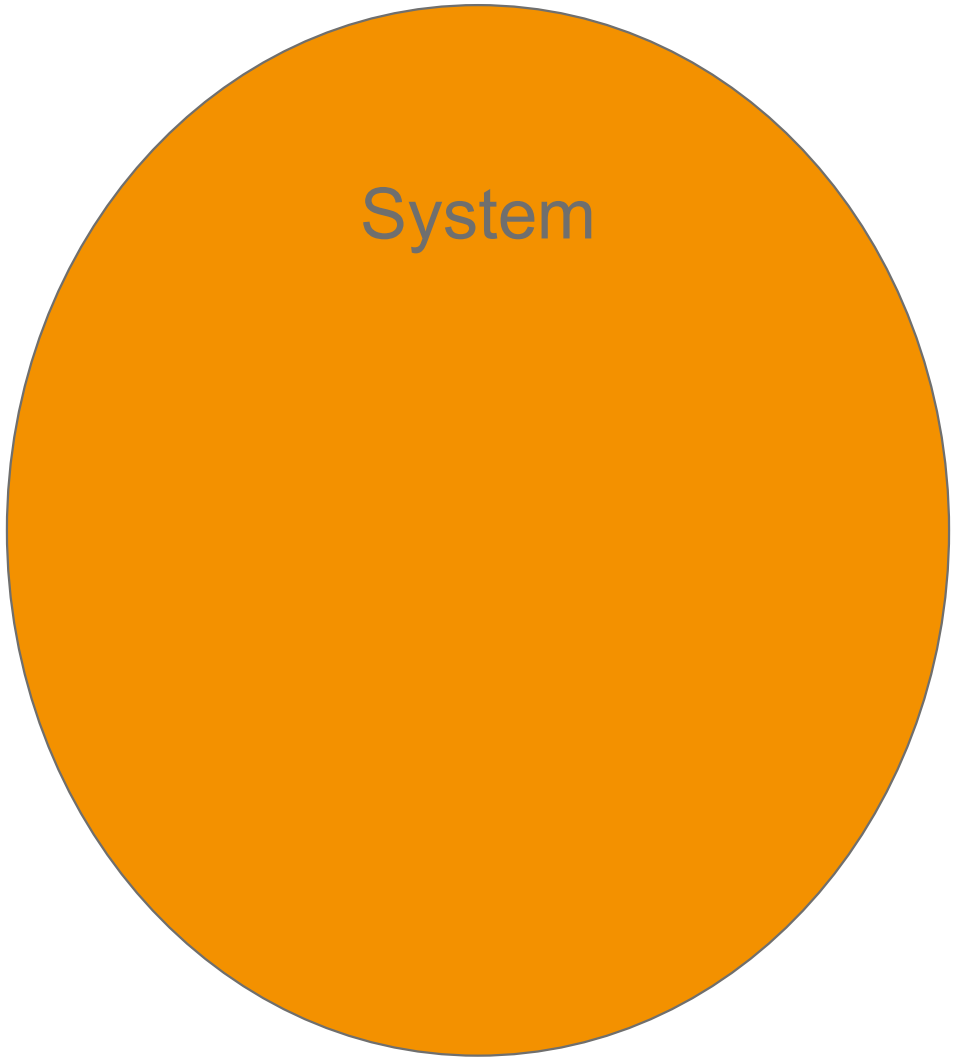
System

- A **system** is an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements. (1)

- A **system** is a combination of interacting elements organized to achieve one or more stated purposes. (2)

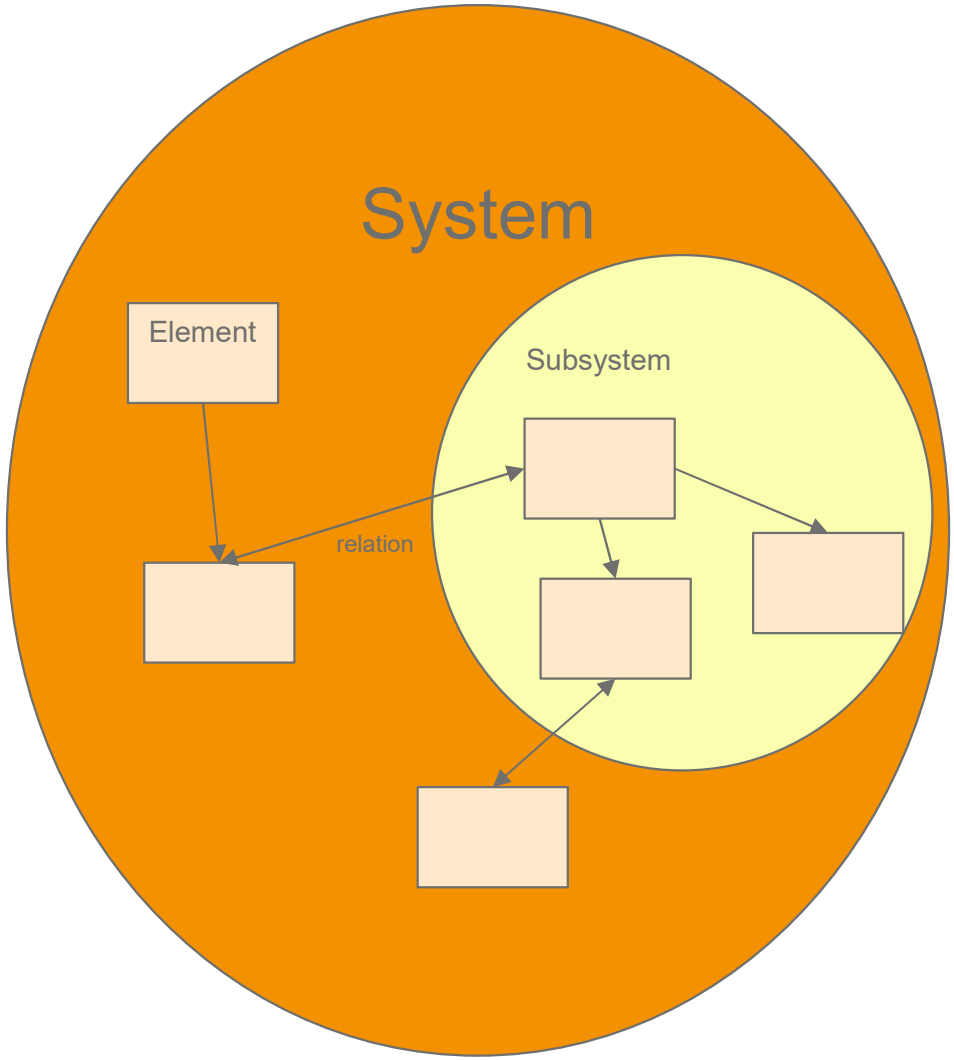


(1) INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

(2) ISO/IEC/IEEE 15288

Element and relations

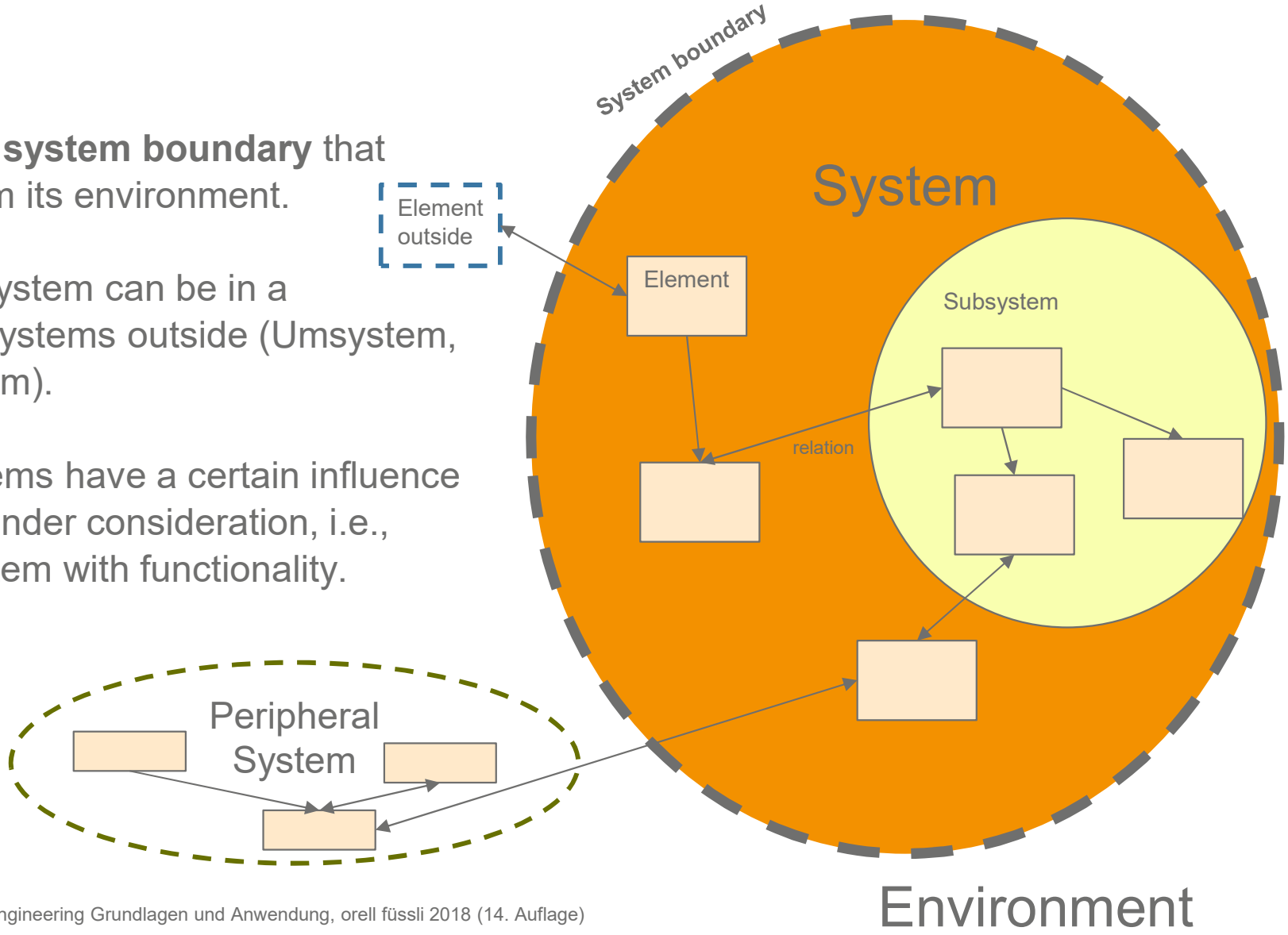
- A system consists of various **elements**.
- An **element** is a component of a system.
- Elements have attributes (properties) and behaviours (to fulfil a specific purpose).
- Elements can be systems, too (subsystem).
- Elements are related to each other – **relation.**



(1) Haberfellner et al., Systems Engineering Grundlagen und Anwendung, orell füssli 2018 (14. Auflage)

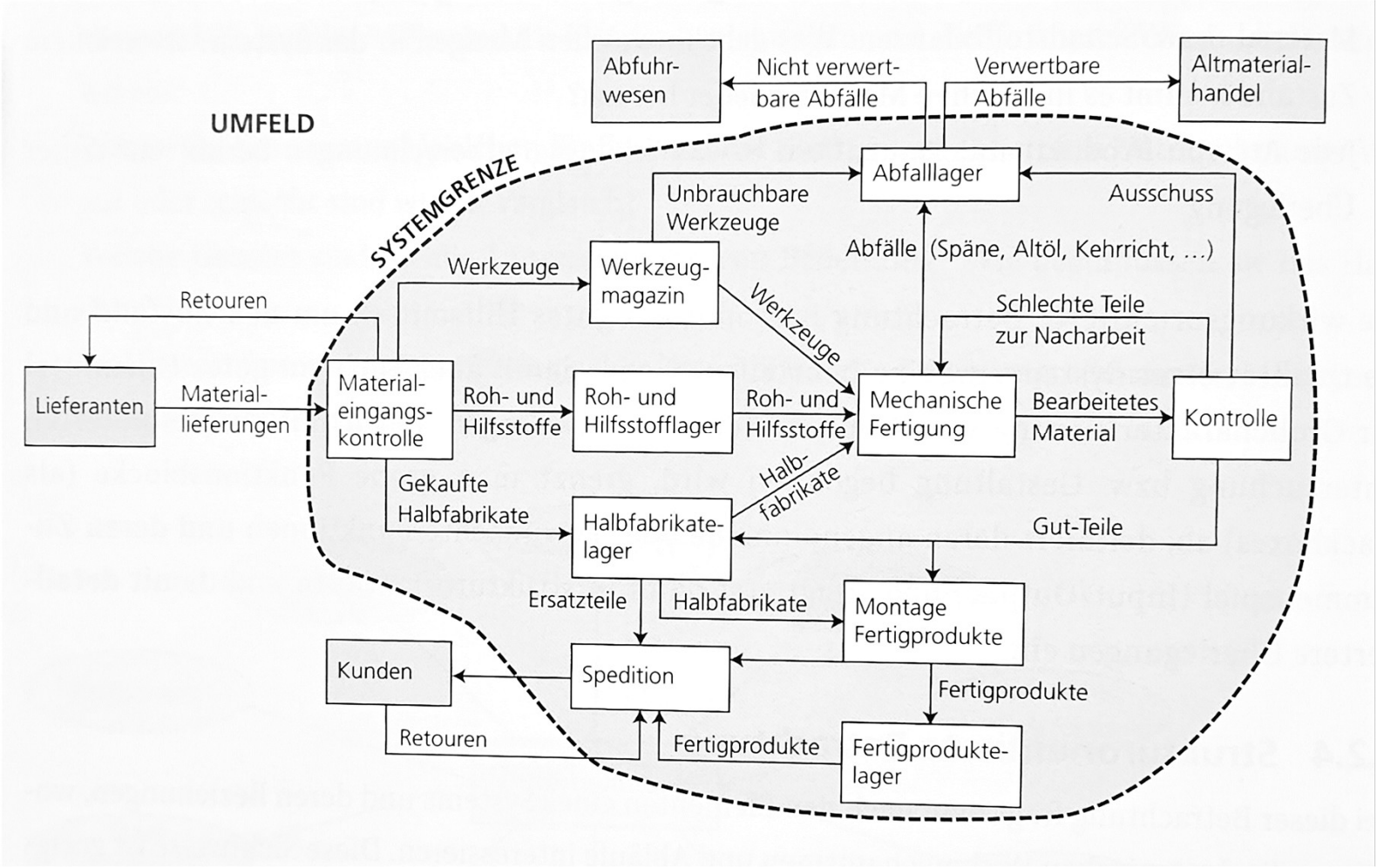
System boundary and environment

- A system has a **system boundary** that separates it from its environment.
- Elements of a system can be in a relationship to systems outside (Umsystem, peripheral system).
- Peripheral systems have a certain influence on the system under consideration, i.e., support the system with functionality.



(1) Haberfellner et al., Systems Engineering Grundlagen und Anwendung, orell füssli 2018 (14. Auflage)

Example of a System



System with viewpoint “Material Flow”

(1) Haberfellner et al., Systems Engineering Grundlagen und Anwendung, orell füssli 2018 (14. Auflage)

System of Systems

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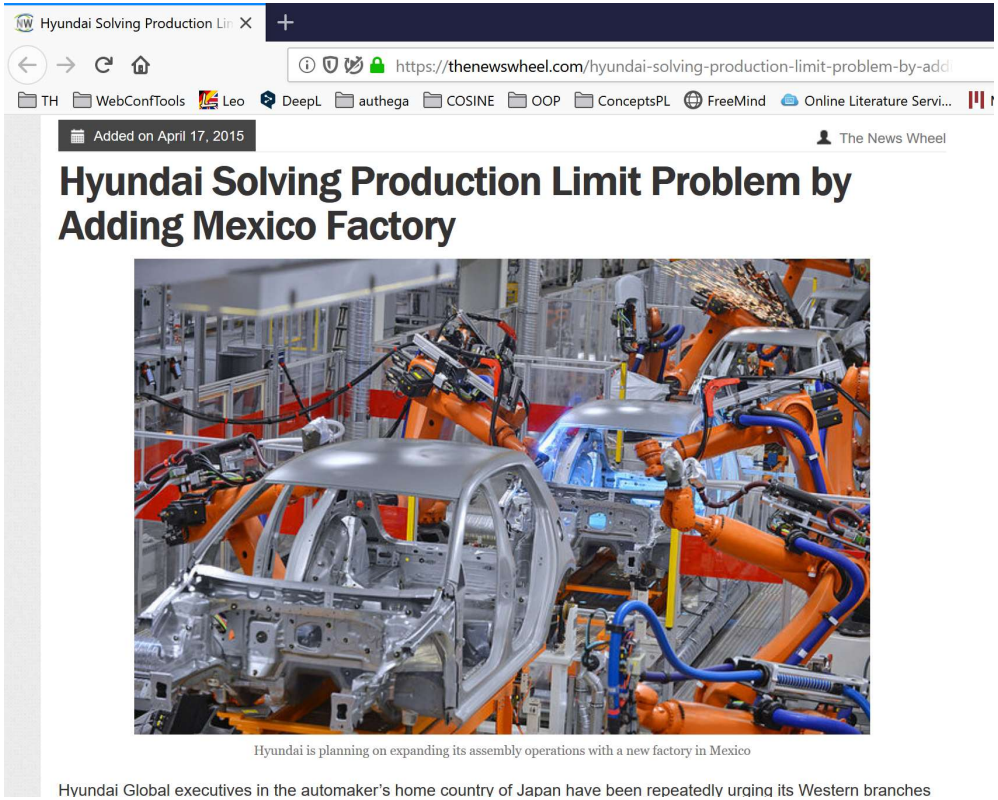
“ … A system of systems (SOS) is a system of interest whose elements are managerially and/or operationally independent systems. These interoperating and/or integrated collections of constituent systems usually produce results unachievable by the individual systems alone. …” (1)

Characteristics of a System of System:

- Subsystems are independent when they operate themselves
- The subsystems can be geographically distributed
- Emergent behavior
- Evolutionary development processes



(1) INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

Example of a system of systems

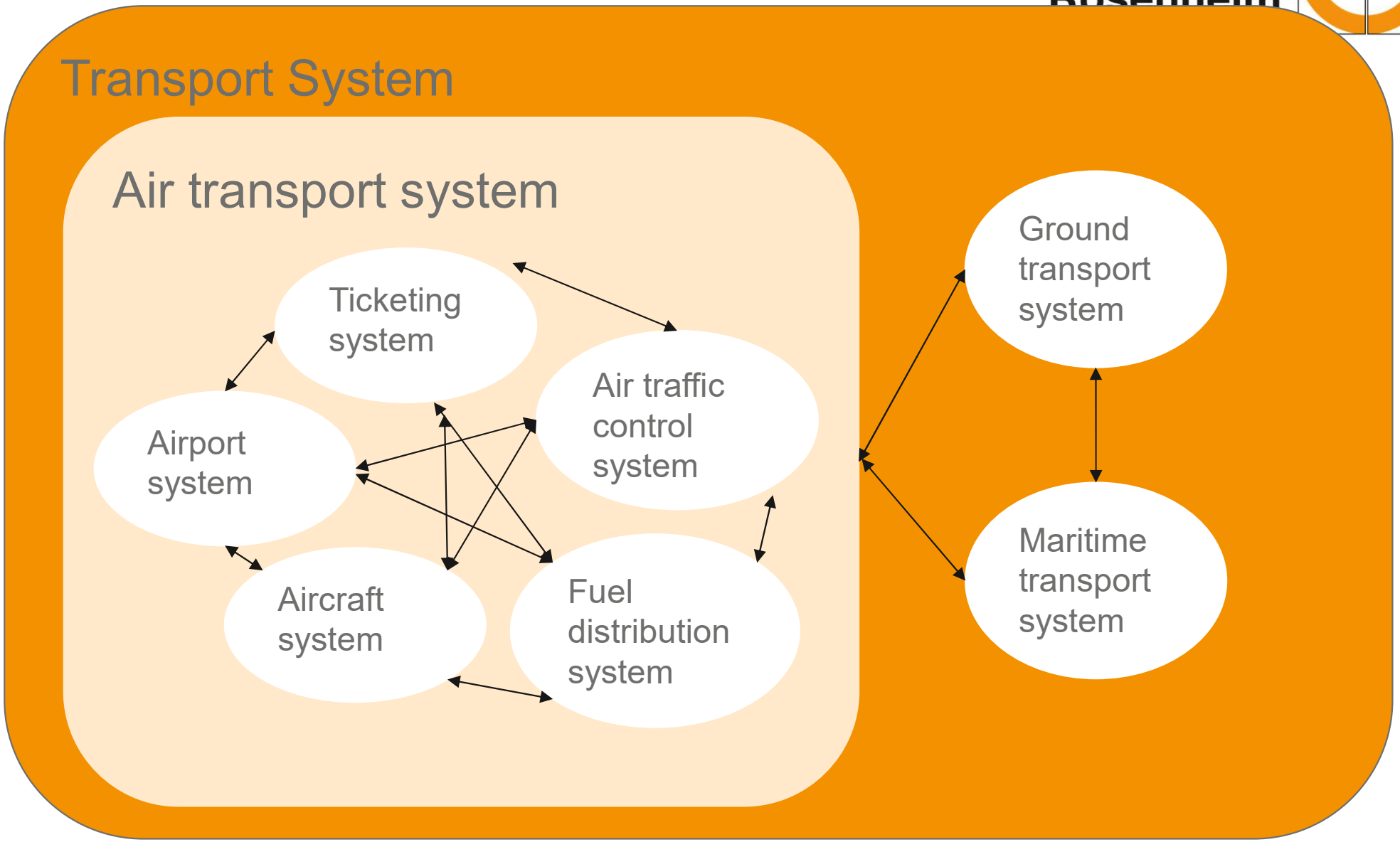


Image redrawn from INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

System properties

- A system exists in a broader context: it is embedded in an environment such as an operational environment.
- A system is composed of several interacting components. These include, for example, HW, SW, processes, system services, people, other organizations, and so on.
- A system has emergent properties: Properties that only arise from the system's interconnection.
- A system goes through a life cycle and fulfils certain functionality with certain behavior and performance.
- A system adapts to its environment. It must therefore be able to change.

Complicated or complex?

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- Complicated or complex, is there a difference?

- Let's check: https://youtu.be/M7Hf6VfsJ0U

Complicated Systems

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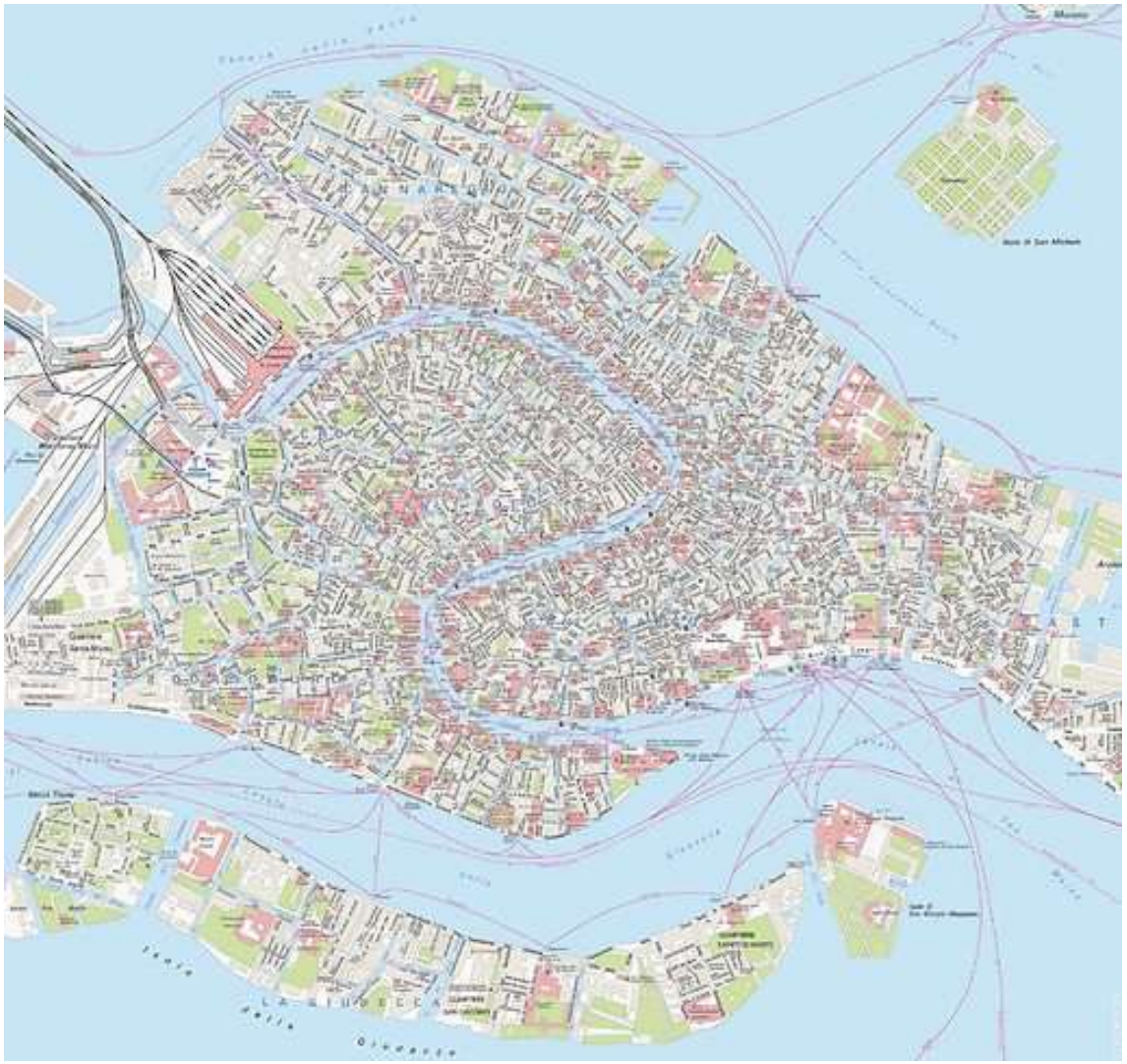
" … Typically, a complicated system is **difficult to be overlooked**, … a persistent analysis allows it to be broken down into subunits to dissolve the 'entanglement'. …" (1)

"… In complicated systems, the interaction between the many parts are governed by **fixed relationships**. This allows reasonably reliable prediction of technical, time and cost issues …" (2)

To understand complicated systems, the system is successively divided into smaller subsystems. This happens until the subsystems have been broken down into simple and smallest building blocks. A smallest building block is achieved, if it can be understood in its individual form. After decomposition, the individual building blocks are then put back together again until the complete overall system is reached.

Sources
(1) Richter et al., Komplexe Systeme, Fischer Kompakt, 2014
(2) INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

Complicated or complex?



https://www.extratapete.de/stadtplaene/venedig3

Map of Complexity Sciences

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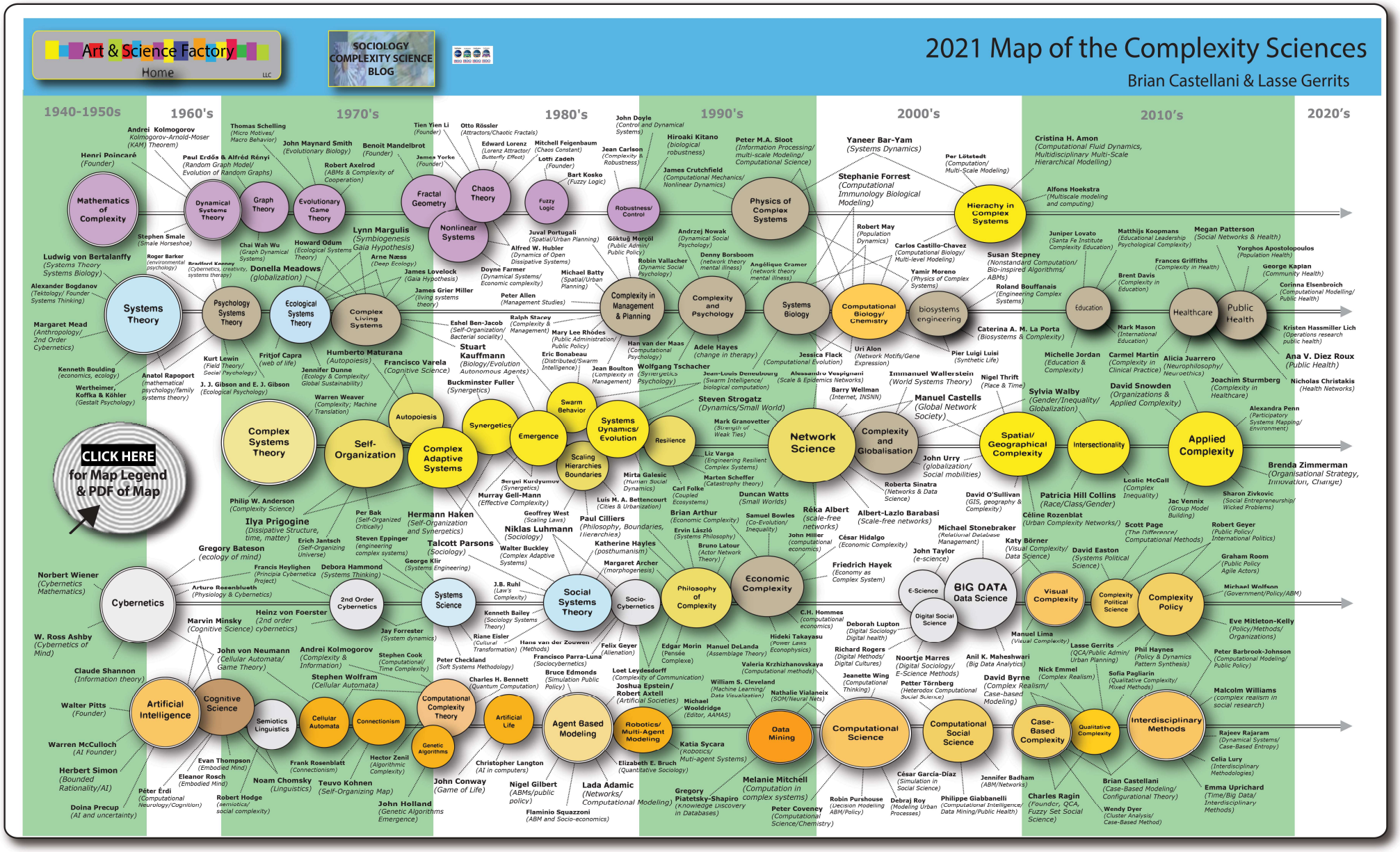

Source: Brian Castellani (2021), "2021 Map of the complexity Sciences", Art & Science Factory, https://www.art-sciencefactory.com/complexity-map_feb09.html

Map of Complexity Sciences: Legend - https://www.art-sciencefactory.com/MapLegend.html

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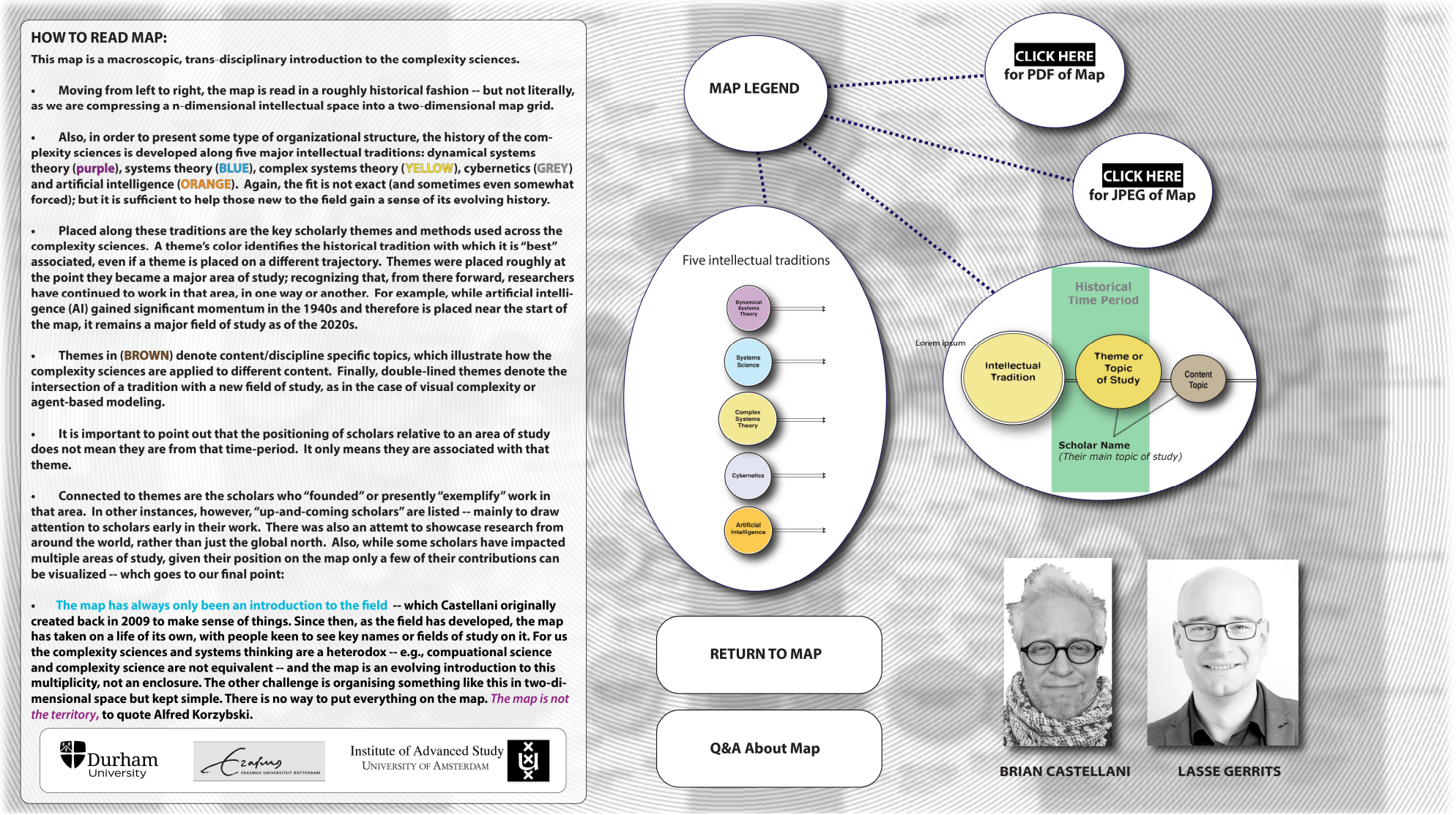
HOW TO READ MAP:

This map is a macroscopic, trans-disciplinary introduction to the complexity sciences.

- **Moving from left to right, the map is read in a roughly historical fashion -- but not literally, as we are compressing a n-dimensional intellectual space into a two-dimensional map grid.**
- **Also, in order to present some type of organizational structure, the history of the complexity sciences is developed along five major intellectual traditions: dynamical systems theory (purple), systems theory (BLUE), complex systems theory (YELLOW), cybernetics (GREY) and artificial intelligence (ORANGE). Again, the fit is not exact (and sometimes even somewhat forced); but it is sufficient to help those new to the field gain a sense of its evolving history.**
- **Placed along these traditions are the key scholarly themes and methods used across the complexity sciences. A theme's color identifies the historical tradition with which it is "best" associated, even if a theme is placed on a different trajectory. Themes were placed roughly at the point they became a major area of study; recognizing that, from there forward, researchers have continued to work in that area, in one way or another. For example, while artificial intelligence (AI) gained significant momentum in the 1940s and therefore is placed near the start of the map, it remains a major field of study as of the 2020s.**
- **Themes in (BROWN) denote content/discipline specific topics, which illustrate how the complexity sciences are applied to different content. Finally, double-lined themes denote the intersection of a tradition with a new field of study, as in the case of visual complexity or agent-based modeling.**
- **It is important to point out that the positioning of scholars relative to an area of study does not mean they are from that time-period. It only means they are associated with that theme.**
- **Connected to themes are the scholars who "founded" or presently "exemplify" work in that area. In other instances, however, "up-and-coming scholars" are listed -- mainly to draw attention to scholars early in their work. There was also an attemt to showcase research from around the world, rather than just the global north. Also, while some scholars have impacted multiple areas of study, given their position on the map only a few of their contributions can be visualized -- whch goes to our final point:**
- **The map has always only been an introduction to the field -- which Castellani originally created back in 2009 to make sense of things. Since then, as the field has developed, the map has taken on a life of its own, with people keen to see key names or fields of study on it. For us the complexity sciences and systems thinking are a heterodox -- e.g., compuational science and complexity science are not equivalent -- and the map is an evolving introduction to this multiplicity, not an enclosure. The other challenge is organising something like this in two-dimensional space but kept simple. There is no way to put everything on the map. *The map is not the territory*, to quote Alfred Korzybski.**

Durham University · Erasmus University Rotterdam · Institute of Advanced Study, University of Amsterdam



Complex Systems

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“ … A complex system is better described as a **'multilayered' system**, … , the system is characterized through **the interconnection of individual parts so that essential properties of the overall system are characterized,** which are either not captured or do not exist at all with the help of the separated parts. …” (1)

“… In complex systems, interactions between the parts to exhibit self-organization, where local interactions give rise to novel, non-local emergent patterns. …” (2)

“ … Complicated systems can often become complex systems when the behavior change, but even systems of very few parts can sometimes exhibit surprising complexity. …” (2)

Sources
(1) Richter et al., Komplexe Systeme, Fischer Kompakt, 2014
(2) INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

Complex System Examples

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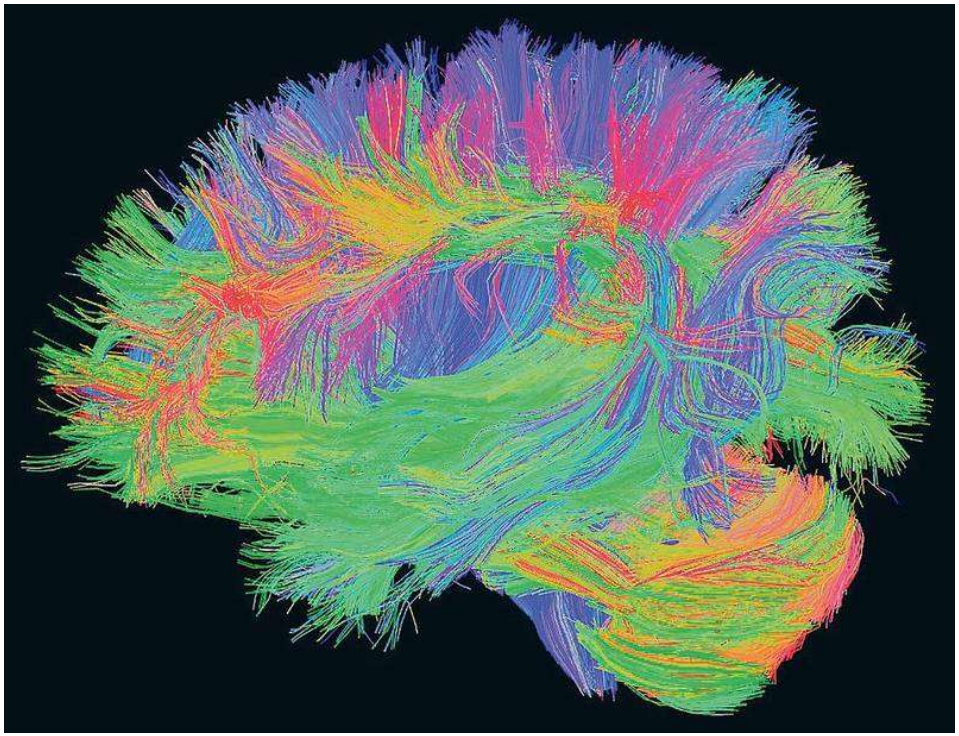
Complexity Theory for change processes

… to develop sophisticated traffic strategies and solutions

Image source: https://www.personalwirtschaft.de/fuehrung/change-management/artikel/serie-new-change-komplexitaetstheorie-bei-change-prozessen.html

The brain as complex neuronal network.

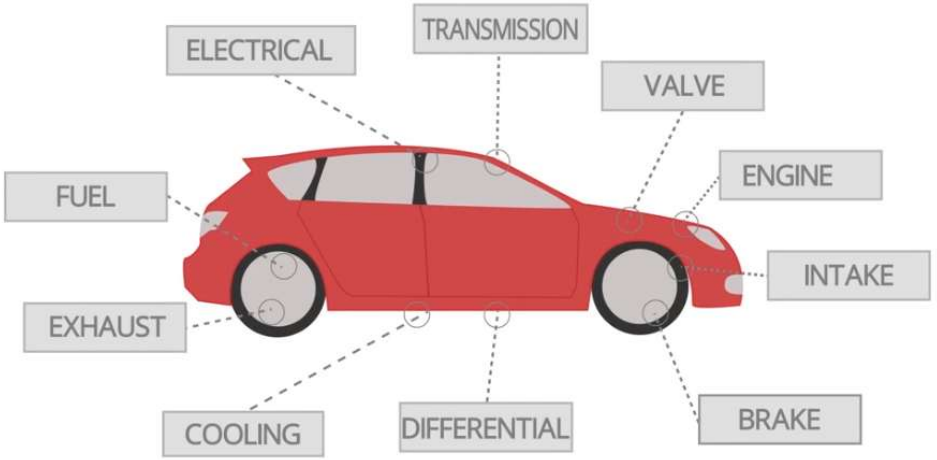


… technical neuronal networks for robotic, image, pattern, -speech recognition

Image source: https://www.tagesspiegel.de/wissen/hirnforschung-mehr-vernetzung-im-alternden-gehirn/22767860.html

Complicated or complex?

https://www.autobild.de/klassik/artikel/aston-martin-von-james-bond-wird-versteigert-1189571.html



MIT - Architecture and Systems Engineering: Models and Methods to Manage Complex Systems

Complexity categories

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- **Structural Complexity** – considers the structure of the system, how system elements are related to each other. It considers the possibilities on how many ways system elements can be combined → can and will the system adapt to external influences?

- **Dynamic Complexity** - considers the dynamic behavior of a system over time, how it behaves in short term (system behavior) versus long term (system evolution)

- **Socio-political Complexity** - considers the effect of people onto a system or the environment a system is operating in. This can consider different point of views of people as by the customer, experience of the people who build or use the system.

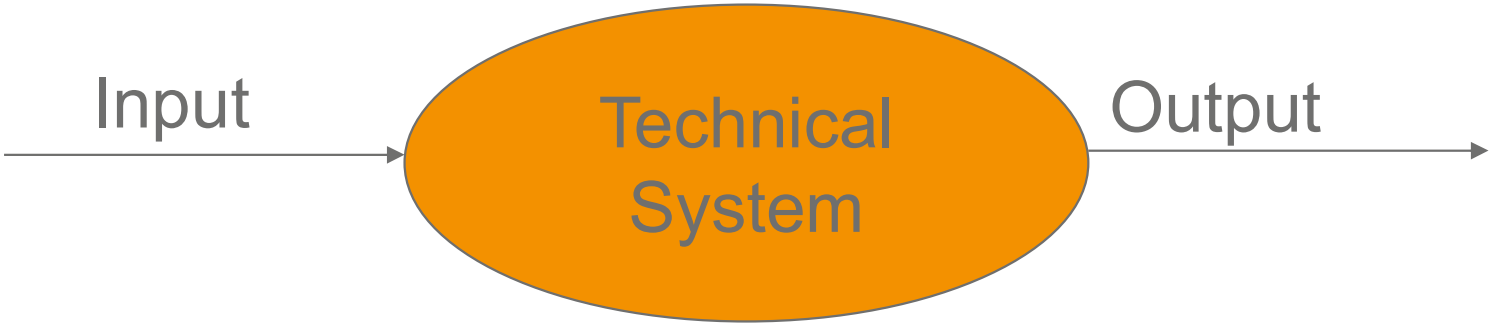
- More reading on complexity and system engineering: https://www.sebokwiki.org/wiki/Complexity

Summary – Review on Complex Systems

- Decentralization
- Hierarchical Structure
- Self-Organization
- Non-Linearity
- Connectivity
- Atomicity and Adaptation
- Core idea: Complex systems consist of many interacting parts whose collective behavior cannot be fully explained by analyzing the individual components alone.

Technical System

- “ … A technical system is characterized by the function of converting, transporting and/or storing substance (material), energy and/or information.
- It is substance specific and consists of materials with defined properties resulting from process engineering.
- A technical systems’ descriptive shape is a spatial structure made up of components.
- The design is carried out in production engineering ... “ (all from 1)



Source: (1) Nina Groß, Entwicklung und Evaluation eines Wissenstransferprozesses für Teams in komplexen technischen Systemen, Kovac Verlag 2017

Characteristics of Technical Systems

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- Ein *System* ist ein Gebilde, das durch *Funktion* und *Struktur* verbunden ist und durch eine Systemgrenze von seiner Umgebung virtuell abgegrenzt werden kann.
- Die *Systemfunktion* besteht in der Überführung operativer Eingangsgrößen in funktionelle Ausgangsgrößen, sie wird getragen von der Struktur des Systems.
- Die *Systemstruktur* besteht aus der Gesamtheit der Systemelemente, ihren Eigenschaften und Wechselwirkungen.

Systemstruktur: $S = \{ A, P, R \}$, mit

A: Systemelemente

$A = \{ a_1, a_2, \ldots, a_n \}$,
(n Anzahl der Elemente)

P: Eigenschaften der Elemente

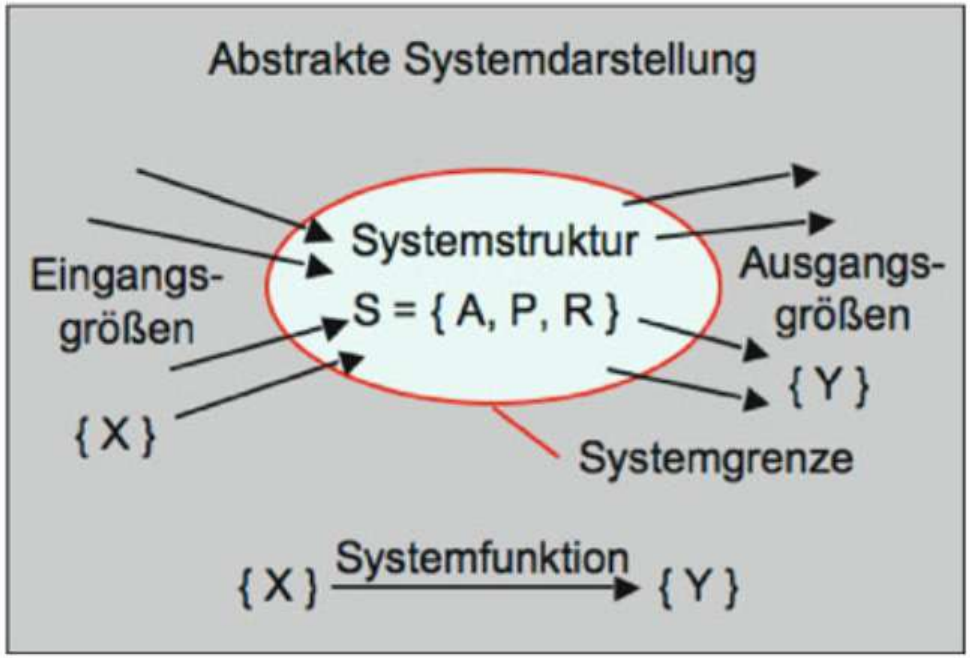
$P = \{ P(a_i) \}$

R: Wechselwirkungen der Elemente

$R = \{ R(a_i, a_j) \}$

Systemfunktion: $\{ X \} \rightarrow \{ Y \}$

X: Eingangsgrößen
Y: Ausgangsgrößen



Source: Horst Czichos, Mechatronik. Grundlagen und Anwendungen technischer Systeme, Lehrbuch, 2015

Simple System Hierarchy

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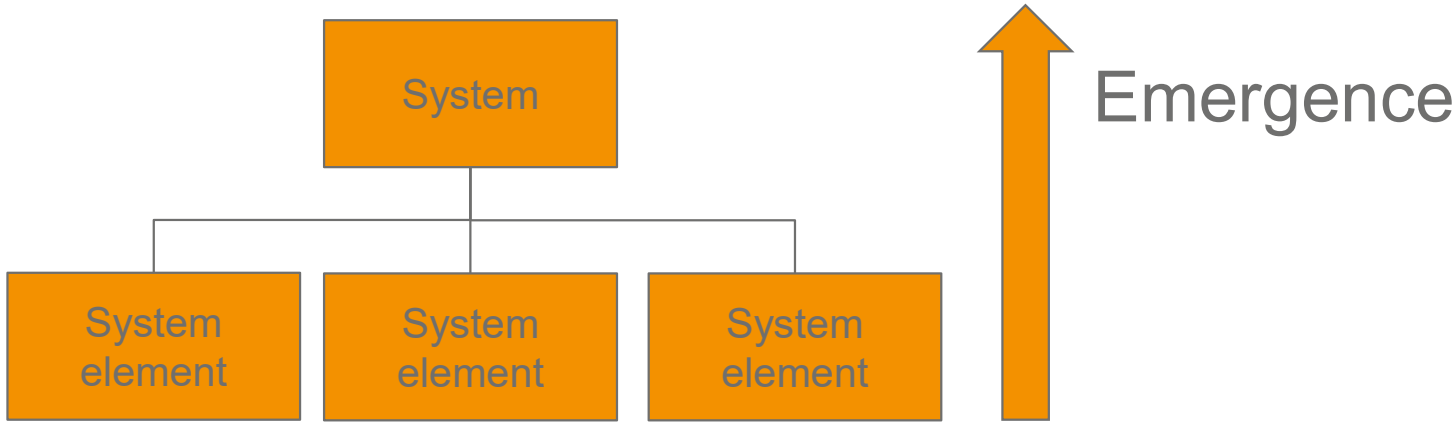
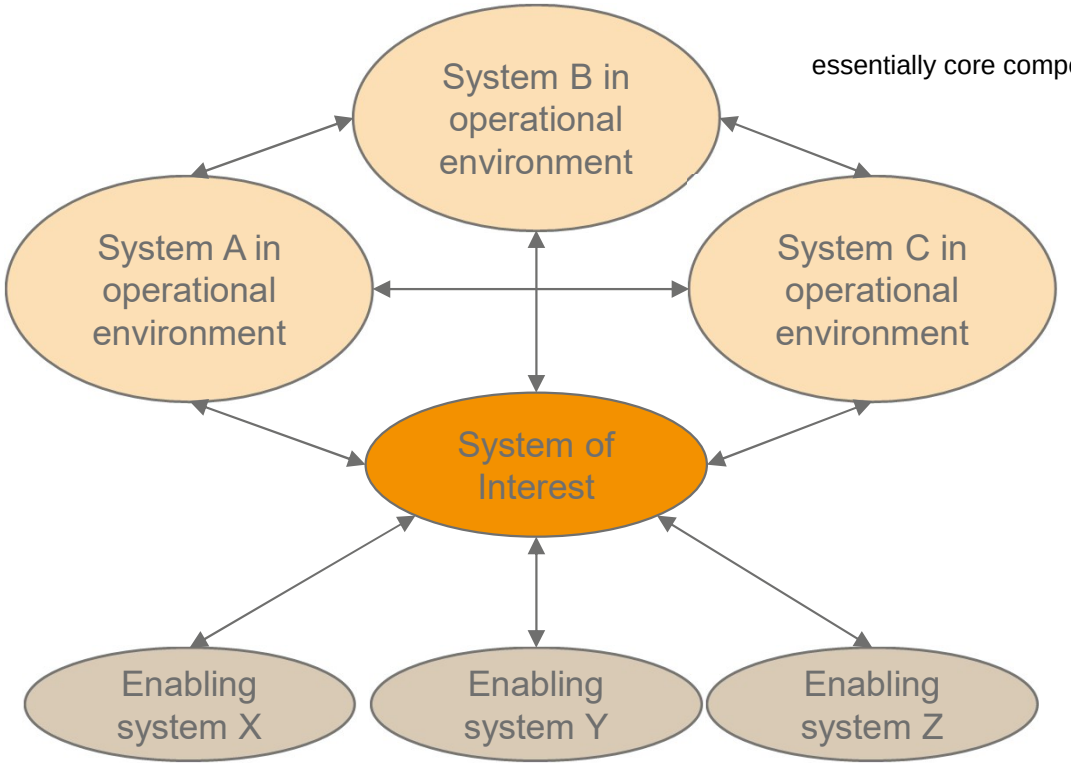
When it comes to system life cycle processes, the systems under investigation are systems decomposed into a set of interacting systems



Source drawing: INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

System of Interest



essentially core components

outside components that were e.g. bought to help the core systems work

System of Interest with its operational environment and enabling systems.

Source drawing: INCOSE, Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Wiley, 2015

Complex technical system

- „ … Complex technical systems are closely coupled, high-risk operating environments …” (1)
- “ … Complex technical systems are developed and implemented under the support of tools and interdisciplinary approaches of Systems Engineering also in large projects. …” (2)
- “ … A complex technical system can also be seen as an artificially rebuilt model of a real-world complex system to achieve a better understanding of complex systems in nature. … “ (3)
- „ … Complex technical systems consist of an organized network of multiple sub-functions with holistic effect ... „ (4)
- A complex technical system is a technical system that has increased in complexity over time, either in terms of the hardware or software involved.
- A complex technical system can also be a combination of many technical systems: systems that interact with each other to achieve a certain result. The results are only achieved by combining the elements of the technical system.

(1) Nina Groß, Entwicklung und Evaluation eines Wissenstransferprozesses für Teams in komplexen technischen Systemen, Kovac Verlag 2017
(2) Systems Engineering entry on Wikipedia https://de.wikipedia.org/wiki/Systems_Engineering
(3) Max Planck Institute about Complex Systems: https://www.mpg.de/96174/cpt08_Komplexe_Systeme.pdf
(4) Günther Spur, Erscheinungsformen und Modelle technischer Systeme: Beitrag zur theoretischen Begründung der Technikwissenschaften; Document found under http://www.wissenschaftsforschung.de/Jb06_Spur.pdf , p.4

Examples

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(1)

(2)

(3)

(4)

(5)

(6)

(1) https://mojix.com/7-ways-rfid-automotive-manufacturing/
(2) https://www.dailytelegraph.com.au/inside-the-biggest-building-in-the-world-a-tour-of-the-boeing-factory/news-story/334d7b688b52dcee929e5ccc241dd543
(3) https://blog.vdi.de/2014/05/komplexe-technische-systeme/
(4) https://www.gehealthcare.com/products/magnetic-resonance-imaging/3-0t
(5) https://www.nasa.gov/mission_pages/station/main/index.html
(6) http://large.stanford.edu/courses/2018/ph241/benjamin-addy2/

Summary

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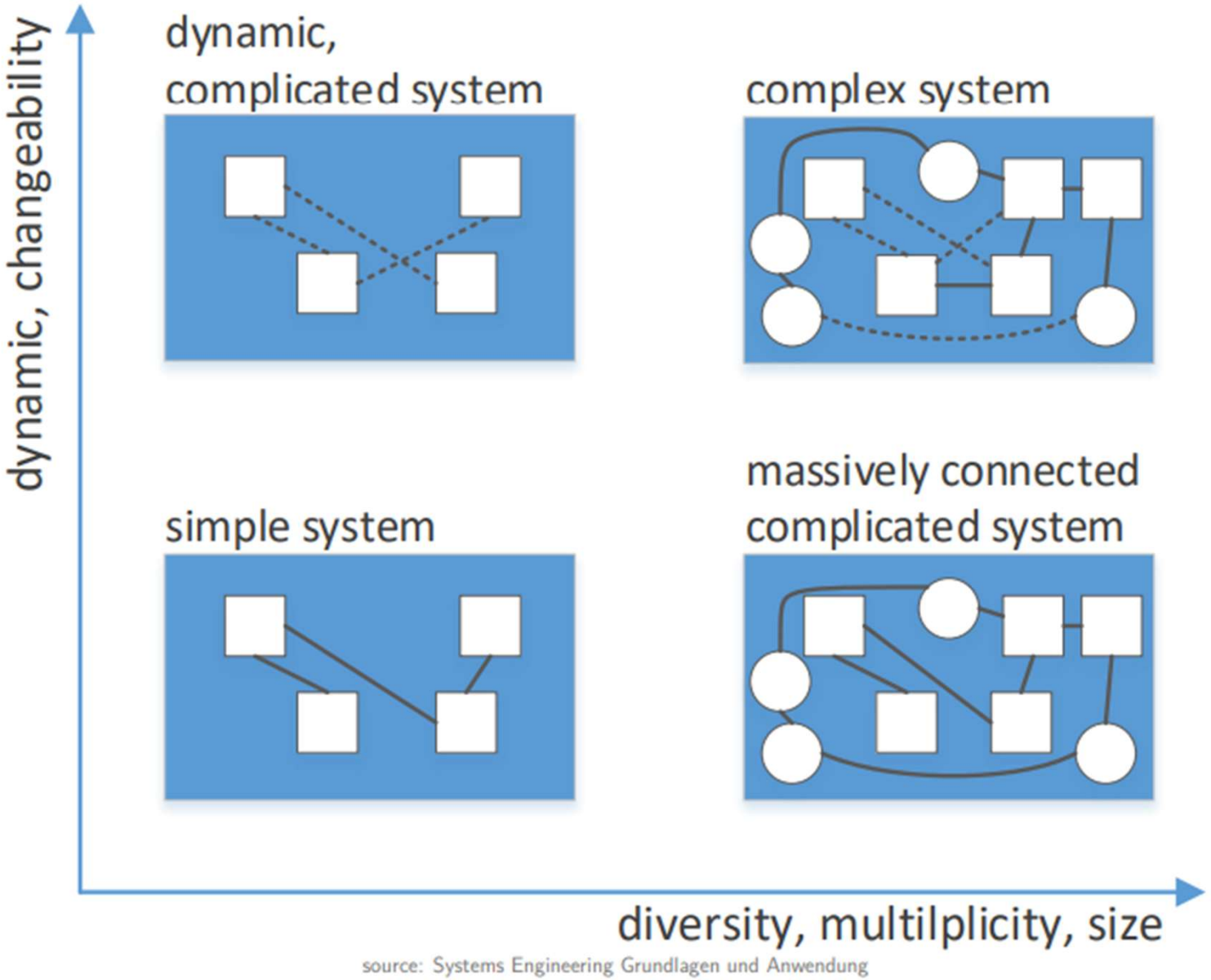
- A **complicated system** is difficult to understand, but based on an analysis, the system can be broken down into subsystems and small subunits, so that the complicated system and its behavior can be understood.

- A **complex system** has connections between individual parts/systems which lead to characteristic properties of the system --- emerging properties: these properties are only present through the connections between them and do not exist in the individual subsystems.
  dynamic and self-organised, cannot predict outcome (non-linear), work towards the same goal

- In terms of systems engineering, complexity has structural (i.e. setup, design), dynamic (i.e. behavior, adaptability) and socio-political (recognition, justifiability of the system) properties.

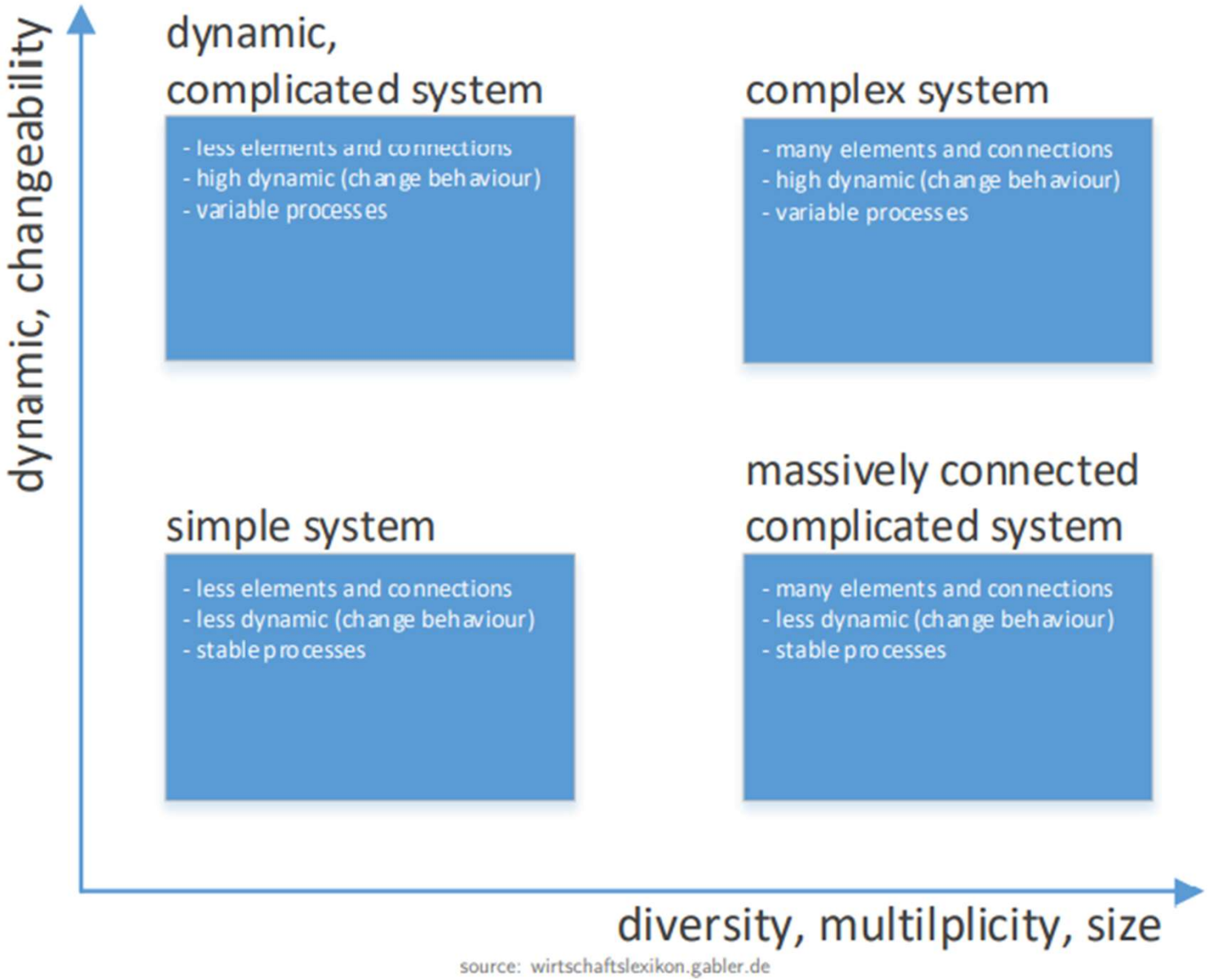
- **Complex technical systems** can either be single systems or systems that are composed of different complex technical systems (system of systems). The composition is done to achieve a certain result. The results are only achieved by the combination of the components or technical systems.

Systems



source: Systems Engineering Grundlagen und Anwendung

Systems



source: wirtschaftslexikon.gabler.de

Time for questions …

Image from: https://pixabay.com