

Introduction to Systems Thinking & Systems Engineering

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Introduction

- In what follows we are going to present basics concepts related to systems thinking and systems engineering.
- The following are two key references for Systems Engineering (SE) related topics:
 - The Systems Engineering Handbook from the International Council on Systems Engineering (INCOSE).
 - The Systems Engineering Body of Knowledge (SEBoK).
- The Systems Engineering Handbook from INCOSE was used extensively while preparing the slides corresponding to this topic.

What is a System?

- “A system is a set of elements in interaction.” (Bertalanffy, 1968) – General definition applicable to any discipline.
- A system is a combination of interacting elements organized to achieve one or more stated purposes. (ISO/IEC/IEEE 15288)
- A system is an integrated set of elements, sub-systems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements. (INCOSE)

What is System?

- Fundamental idea:

A system is a purposeful whole that consists of interacting parts.

- Notice that all the definitions considered provide an internal view of the system.
- Commonly used acronym: SOI = System of Interest.
- Here we are going to focus on systems that are man-made, created and utilized to provide products or services in defined environments for the benefit of users and other stakeholders.

What is a System Element?

- Notice that the definitions of system that were provided make reference to “system elements”:
 - “A system is a **set of elements** in interaction.” (Bertalanffy, 1968)
 - A system is a combination of **interacting elements** organized to achieve one or more stated purposes. (ISO/IEC/IEEE 15288)
 - A system is an integrated **set of elements**, sub-systems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements. (INCOSE)

What is a System Element?

- The following is from the definition of system element provided in the glossary of terms of the SEBoK:
 - **A system element is a discrete part of a system that can be implemented to fulfill specified requirements.**
 - A system element can be hardware, software, data, humans, processes (e.g., processes for providing service to users), procedures (e.g., operator instructions), facilities, materials, and naturally occurring entities (e.g., water, organisms, minerals), or any combination. (ISO/IEC 15288:2015)

Some Key Principles of a System

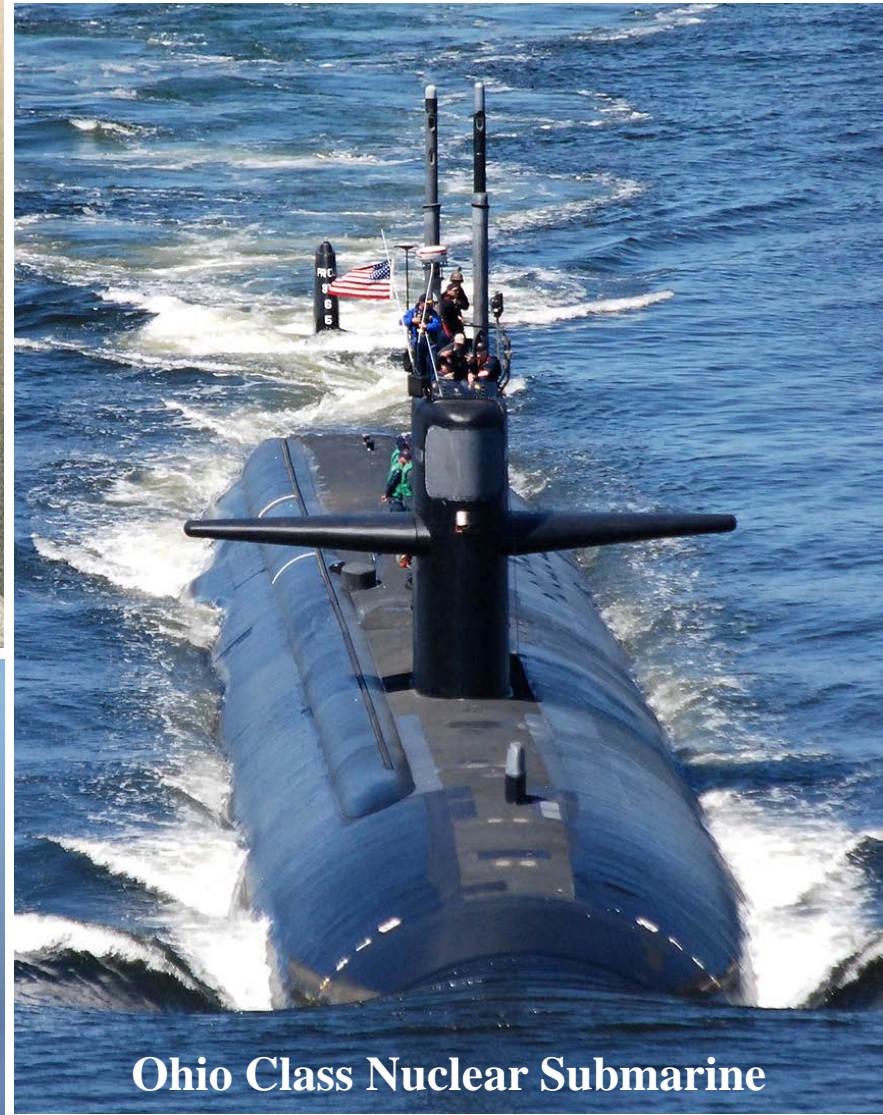
- A system is more than the sum of its parts.
- A system is no better than its weakest link.
- Optimizing the parts will not optimize the whole.
- Interactions determine the performance of a system.
- As the number of elements in a system grow, the number of interactions quickly outgrows the number of elements.

Different Systems

2017 Ford Mustang



Boeing 787-10



Ohio Class Nuclear Submarine

Different Systems



The iBOT

- For several of the concepts that we are going to present we will be using the iBOT as an example.
- The iBOT is a revolutionary motorized wheelchair with two sets of powered wheels that can be rotated to allow the user to “walk” up and down stairs. The wheelchair allows users to rise from a sitting level to approximately six feet in height and travel in this "standing" configuration, and is capable of traveling through a wide variety of terrain types.
- In what follows, we will present a little bit of information about the iBOT so that you can become familiar with it.

The iBOT



The iBOT



iBOT: Background

- Designed by DEKA in conjunction with Johnson and Johnson to revolutionize wheelchairs.
 - DEKA also is responsible for FIRST robotics and, not coincidentally, the Segway.
- Introduced on Dateline NBC in 1999.
- Clinical trials completed 2002.
 - Unanimous FDA approval 2003.



iBOT: Background

- Discontinued in 2009 by Johnson and Johnson.
 - Only a few hundred sold / year.
 - Retail price: \$25,000; Medicare payment: \$5,000.
 - Veterans' organization America's Huey 091 Foundation pushed for reinstatement with support from DEKA .

- Revived in 2014.
 - FDA reclassification from Class III to Class II.
 - Lowered cost of regulations now makes the project economically viable.

iBOT: Features

- Stair climbing.
 - Requires a bit of upper arm strength – somewhat limits customer base.
 - This is also “scary” – one of the weaknesses of the iBOT.
- Standing.
 - Allows reaching high shelves, seeing others eye-to-eye.
 - Can travel in this configuration at low speeds.
- Terrain performance.
 - 4WD operation.
 - Can drive in sand / gravel / puddles.
 - Can climb small curbs.

iBOT: Features

- Remote operation
 - Can load into vehicles from the front seat.
- Promotional video:



<https://www.youtube.com/watch?v=O7otewMk9pc>

iBOT: User Testimonials

- “This wheelchair has changed my life forever. I can reach things that were unreachable. I can look people in the eye while talking to them. I can traverse rough terrain that my old wheelchair would only get stuck in like gravel and sand. I can sail over curbs - no more dodging the traffic to get to the next curb cut. I can even do stairs!”
- “It has transformed my life. There isn't a day that has gone by that I haven't thought, ‘Oh, my gosh, I wouldn't be able to do this if I weren't in my iBOT right now.’”
- “I don't consider it a wheelchair. It's almost like robotic skin. With this iBOT, I don't feel like I'm disabled. I just feel like I'm inconvenienced.”
- “If I ever had to get out of this chair, I really don't know if I'd want to live anymore, to be honest with you.”

What Went Wrong?

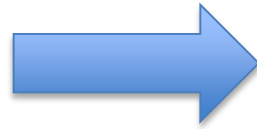
- The iBOT was released to great fanfare.
- Extensive research was done on requirements for the disabled.
 - By all accounts the product was successful in meeting the needs.
- FDA approval was achieved at Class III (high risk) status early on.
 - This was expected – a high regulatory burden is natural for a device like this.

What Went Wrong?

- The issue? Medicare
 - Quality of life features are not “medically necessary”.
 - Medicare treats this as a basic electric wheelchair – the disabled must pay ~\$20k out of pocket.
- The Medicare reimbursement issue unexpectedly shrank the demand, which led to discontinuation.

The iBOT Legacy

- Much of the iBOT technology made its way into the Segway.
 - Interesting fact: The owner of Segway died after accidentally riding his Segway off a cliff.
 - “Hoverboards” operate on the same principles.
- Less innovation in quality of life technology.



The Future of the iBOT

- In May 2016 Toyota announced that it is joining forces with DEKA to “support mobility solutions for the disabled community.”
- This includes developing and launching the next generation of the iBOT.

The Future of the iBOT



<http://www.theverge.com/circuitbreaker/2016/5/23/11744714/ibot-wheelchair-toyota-dean-kamen-revival>

Operating Environment or Context of a System

- The operating environment or context of a system is the collection of elements that specifically do not belong to the system but that interact with the system. It can include the users (or operators) of the system.
- The functionality of a system is typically expressed in terms of the interactions of the system with its operating environment.
- The operating environment provides an external view of the system.

Operating Environment or Context of a System

- iBOT Environment:
 - Users.
 - Existing infrastructure: homes, buildings, electric grid, etc.
 - Terrain / stairs.
 - Others.



System Boundary

- The internal and external views of a system give rise to the concept of a system boundary.
- The system boundary is a “line of demarcation” between the system itself and its context (operating environment).
- It defines what belongs to the system and what does.
- It must not be confused with the subset of system elements that interact with the environment.

System Boundary

- iBOT Boundary:
The outer surface of the device + the recharging cable.



What is an Interface?

- Different disciplines have definitions that are applicable in a particular context.
- Here we consider a couple of them.
- A shared boundary between two functional units, defined by various characteristics pertaining to the functions, physical signal exchanges, and other characteristics. (ISO/IEC 1993)
- A hardware or software component that connects two or more other components for the purpose of passing information from one to the other. (ISO/IEC 1993)

What is an interface?

- Internal interfaces: Between the system elements composing the system.
- External interfaces: Between the system elements and the elements outside the SOI.
- Defining the logical and physical aspects of internal and external interfaces requires careful consideration and is an important aspect in the design of a system.
- How to connect the elements of a system cannot be an afterthought!

System Stakeholders

- A stakeholder is an individual or organization having a right, share, claim, or interest in a system or in its possession of characteristics that meet their needs and expectations. (ISO/IEC June 2010)
- Stakeholders include, but are not limited to end users, end user organizations, supporters, developers, producers, trainers, maintainers, disposers, acquirers, customers, operators, supplier organizations and regulatory bodies. (ISO/IEC June 2010)

System Stakeholders

- iBOT Stakeholders:
 - Users
 - Government Regulators
 - Insurance Groups
 - Healthcare Workers
 - Distributors
 - Manufacturer
 - ...

Important Terminology

- An ***attribute*** of a system (or system element) is an observable characteristic or property of the system (or system element).
- A ***variable*** is a symbol or name that identifies an attribute.
- A ***measurement*** is the outcome of a process in which the SOI interacts with an observation system under specified conditions.
- The outcome of a measurement is the assignment of a value to a variable.

Important Terminology

- A system is in a ***state*** when the values assigned to its attributes remain constant or steady for a meaningful period of time (Kaposi and Myers, 2001).
- System elements can have ***processes*** in addition to attributes. Those process can be assigned the binary logical values of being either idle or executing.
- The above is particularly true when some of the system elements are software objects.
- A complete description of a system state requires values to be assigned to both attributes and processes.

Important Terminology

- ***Dynamic behavior*** of a system is the time evolution of the system state.
- ***Emergent behavior*** is a behavior of the system that cannot be understood exclusively in terms of the behavior of the individual system elements.
- ***Black box/white box*** system representation.
 - The black box representation is based on an external view of the system (attributes).
 - The white box representation is based on an internal view of the system (attributes and structure of the elements).

Hierarchy within a System

- One of the challenges of system definition is to understand what level of detail is necessary to define each system element and the interrelations between elements.
- System elements can be “atomic” (i.e., not further decomposed) or they can be systems on their own merit (i.e., decomposed into further subordinate elements).
- A system element that needs only a black box representation (external view) to capture its requirements and confidently specify its real-world solution definition can be regarded as “atomic”.

Hierarchy within a System

- A ***partitioning*** of a system is a system representation that identifies a complete set of distinct system elements based on their relation to the whole (system), suppressing the details of their interactions and interrelations.
- Hierarchy within a system is an “organizational representation” of system structure using a partitioning relation.
- Urwick (1956) suggests that a possible heuristic is for each level in the hierarchy to have no more than 7 ± 2 elements subordinate to it.

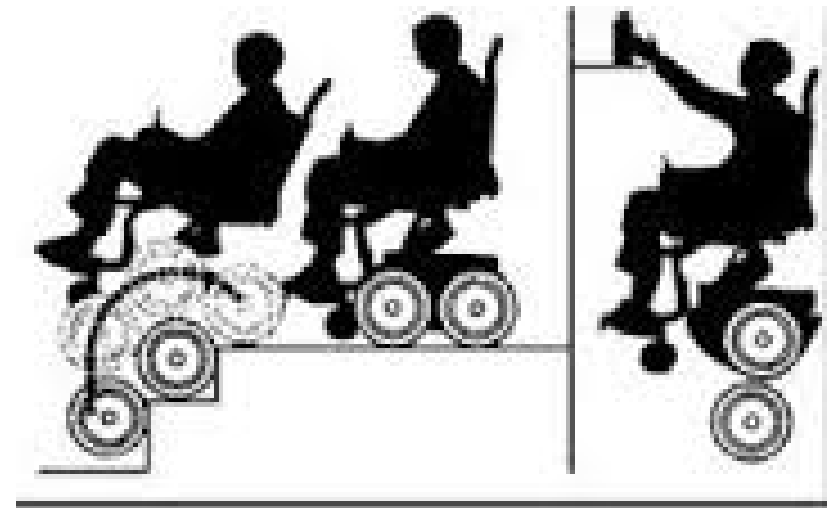
iBOT Subsystems

- The partitioning (decomposition) is not unique.
- Structural
 - Frame
 - Seat
- Propulsion
 - Drive motors
 - Tilt motors (for raising, stair climbing)
 - Wheels



iBOT Subsystems

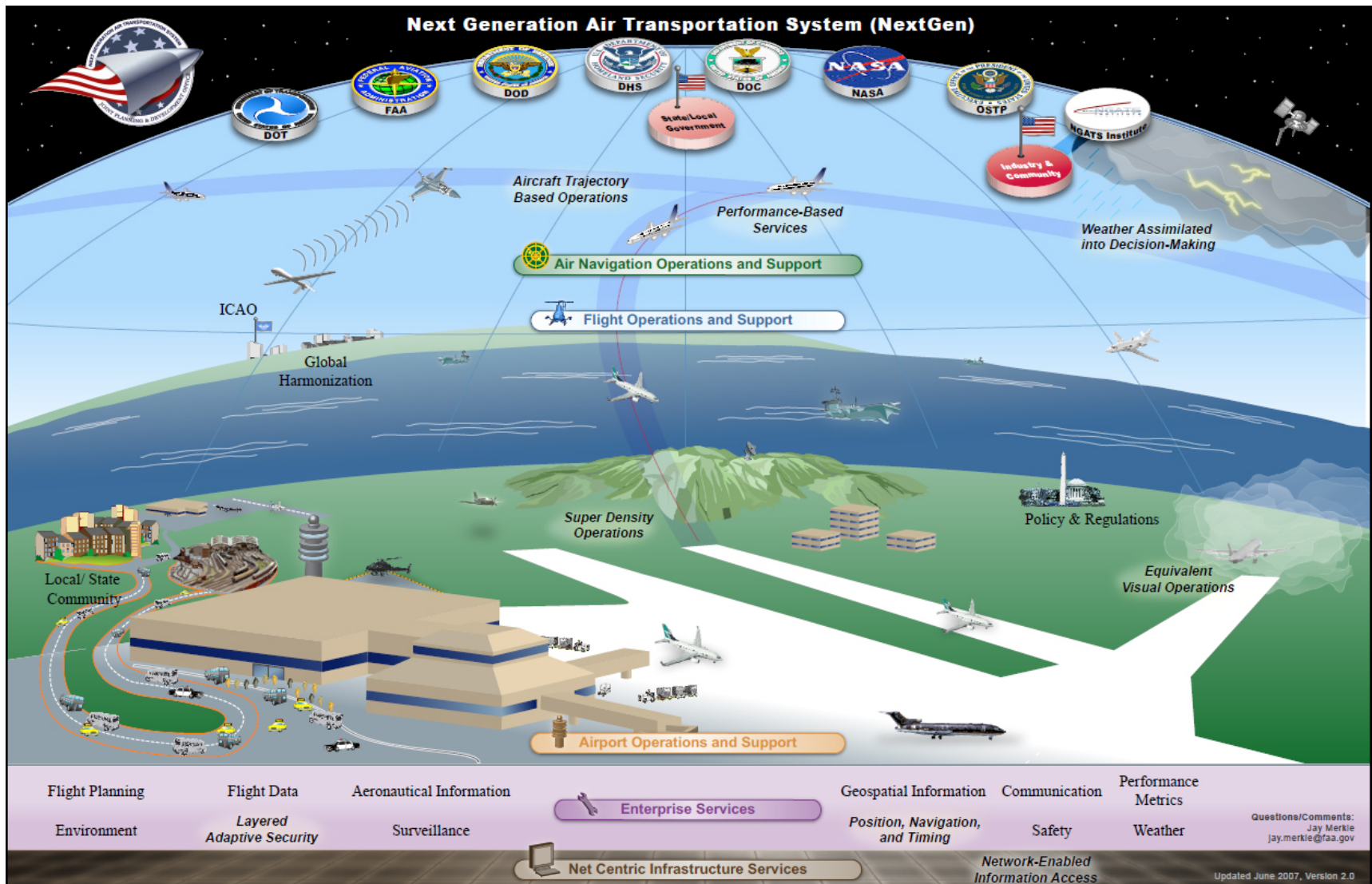
- Control
 - User control panel
 - Sensors (gyros, accelerometers, etc.)
 - Control computer (for upright stabilization / tracking control)
- Power
 - Battery
 - Power distribution electronics
 - Battery recharge system



System of Systems (SoS)

- A “system of systems” (SoS) is an SOI 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 system alone.

System of Systems (SoS)



Systems Engineering (SE)

- Systems engineering (SE) is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. (INCOSE)
- Systems engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system. (Eisner, 2008)

Systems Science

- Systems science brings together research into all aspects of systems with the goal of indentifying, exploring, and understanding patterns of complexity that cross disciplinary fields and areas of application.
- An integrated systems approach for solving problems needs to combine elements of systems science, systems thinking, and SE.
- Classical sciences use a reductionist approach → Separating and isolating in search of simplicity.

Systems Science

- Systems science relies on connecting and contextualizing to identify patterns of organized complexity.
- Emergent properties of a system cannot be understood using a reductionist approach.

Systems Thinking

- Systems thinking is a unique perspective on reality that sharpens our awareness of whole and how the parts within those wholes interrelate → A holistic approach to analysis.
- Holistic: relating to or concerned with wholes or with complete systems rather than with the analysis of, treatment of, or dissection into parts. (Merriam-Webster Dictionary)

Characteristics of a Systems Thinker

(Waters Foundation, 2013)

- Seeks to understand the big picture.
- Observes how elements within the system change over time, generating patterns and trends.
- Recognizes that a system's structure (elements and their interactions) generates behavior.
- Identifies the circular nature of complex cause-and-effect relationships.
- Surfaces and tests assumptions.
- Changes perspectives to increase understanding.
- Considers an issue fully and resists the urge to come to a quick conclusion.
- Considers how mental models affect current reality and the future.

Characteristics of a Systems Thinker

(Waters Foundation, 2013)

- Uses understanding of system structure to identify possible leverage actions.
- Considers both short- and long-term consequences of actions.
- Finds where unintended consequences emerge.
- Recognizes the impact of time delays when exploring cause-and-effect relationships.
- Check results and changes actions if needed: “successive approximations”.

What is Systems Architecting / Systems Architecture?

- The art and science of creating and building systems too complex to be treated by engineering analysis alone. That part of systems development most concerned with scoping, structuring, and certification. A combination of the principles of both systems and of architecting. (Rechtin and Maier, 1997)
- The mapping of function to form through concept. (Crawley, 1999)
- The scheme by which the functional elements of the product are arranged into physical chunks and by which the chunks interact. (Ulrich and Eppinger)

What is Systems Architecting / Systems Architecture?

- The methods used to capture not only what the system requirements are, but also *how* the system will fulfill those requirements. The system architecture model is a cohesive statement of the system's physical configuration in terms of modules, the information flow between them, and their interconnects. (Hatley & Pirbhai, *Strategies for Real-Time System Specification*, 1988)

System Life Cycle

- Every man-made system has a life cycle, even if it is not formally defined.
- In general terms, a life cycle can be defined as the series of stages through which something (a system or manufactured product) passes.
- According to ISO/IEC/IEEE 15288:
Life cycles vary according to the nature, purpose, use and prevailing circumstances of the system ...
- We need to define the life cycle of the SOI and take it into consideration during the design of the system.

System Life Cycle

- Every system lifecycle consists of multiple aspects, including
 - The business aspect (business case)
 - The budget aspect (funding)
 - The technical aspect (product)
- The system life cycle can be divided into stages and decision gates can be used to determine the readiness to move from one stage to the next.
- Decision gates are also known as control gates, “milestones”, or “reviews”.

System Life Cycle

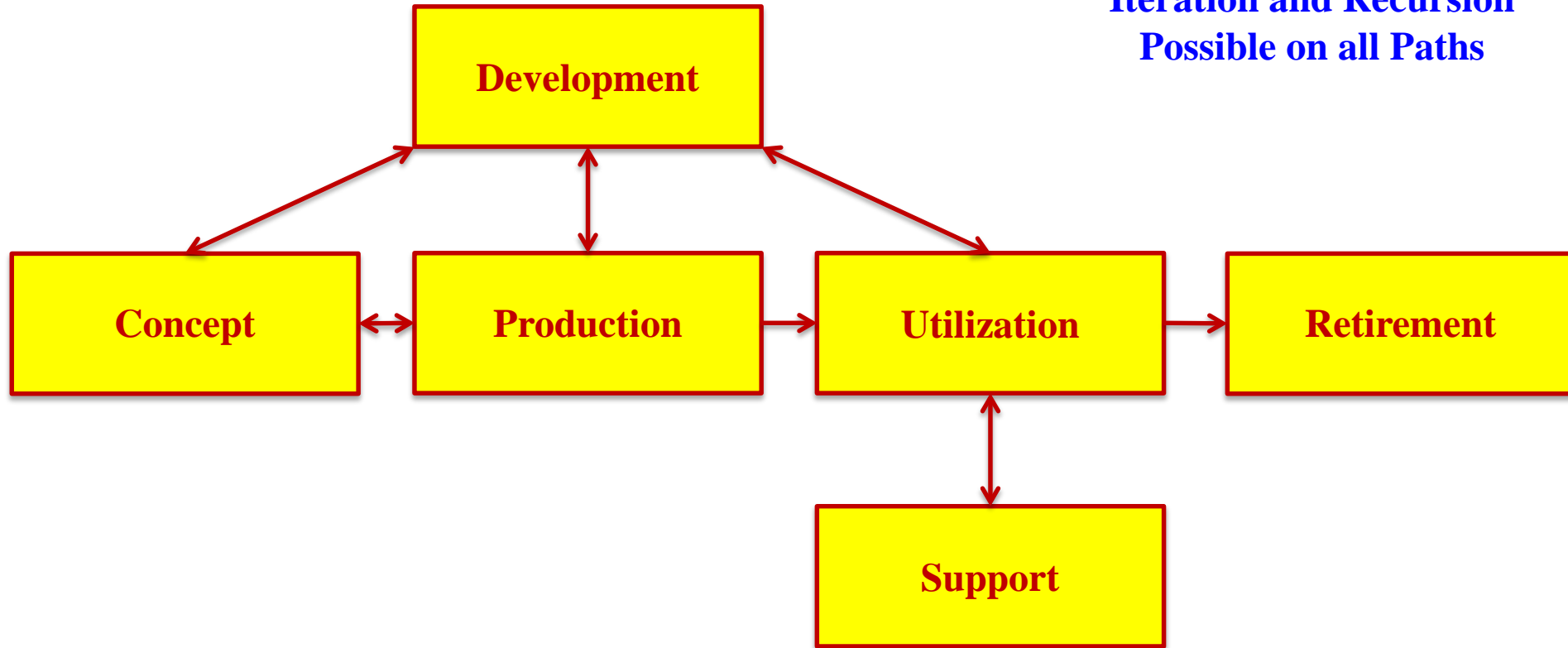
- A decision gate is an approval event in the project cycle that is sufficiently important to be defined and included in the project schedule.
- A decision gate ensures that new activities are not pursued until previously scheduled activities, on which new activities depend, are satisfactorily completed.
- A company or organization needs to define and use a life cycle model that is well suited for the systems that it considers and is consistent with the way in which the company or organization operates.

System Life Cycle

- Here we will consider a generic life cycle model presented in ISO/IEC TR 24748-1, 2010.
- The model consists of the following six life cycle stages:
 - Concept
 - Development
 - Production
 - Utilization
 - Support
 - Retirement
- We will briefly present the purpose of each one.

System Life Cycle

**Iteration and Recursion
Possible on all Paths**



ISO/IEC TR 24748-1 (2010)

System Life Cycle

- Concept Stage
 - Define problem space
 - Characterize solution space
 - Identify stakeholders' needs
 - Explore ideas and technologies
 - Refine stakeholders' needs
 - Explore feasible concepts
 - Propose viable solutions

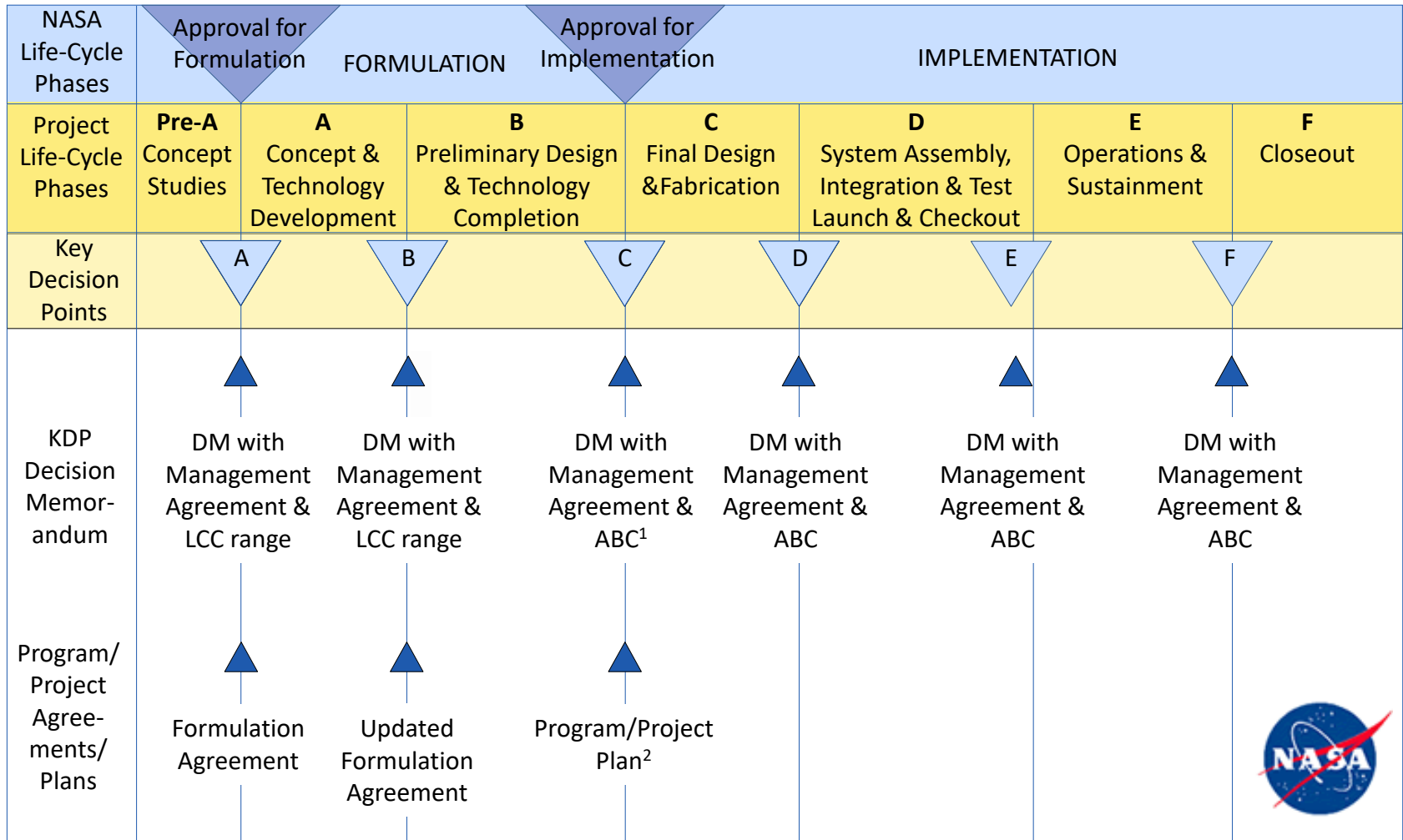
System Life Cycle

- Development Stage
 - Define/refine system requirements
 - Create solution description – architecture and design
 - Implement initial system
 - Integrate, verify, and validate system
- Production Stage
 - Produce systems
 - Inspect and verify
- Utilization Stage
 - Operate system to satisfy users' needs

System Life Cycle

- Support Stage
 - Provide sustained system capability
- Retirement Stage
 - Store, archive, or dispose of the system

NASA Life Cycle Model



¹Changes in the ABC after this point may require a rebaseline review.

²Program/Project Plans are updated as needed during Implementation.

The Systems Engineering “V” Model

- Although different systems engineering models are available, we will only consider the “V” model.
- The “V” model provides a good conceptual framework to introduce ideas such as cascading requirements and system integration, including validation and verification.
- Before presenting the “V” the model, let’s briefly consider the following concepts:
 - Cascading Requirements
 - Verification
 - Validation

Cascading Requirements

- Cascading translates requirements at one level into draft or target requirements at the next lower level, so they in turn can be translated into requirements that will become targets for the next level down.
- Target cascading is a key challenge in early product development: How to propagate desirable product characteristics, defined by product's specifications, to the various subsystems and components in a consistent and efficient manner.
- Consistency means that all parts of the designed system should end up working well together, while efficiency means that the process itself should avoid iterations at later stages, which are costly in time and resources.

Verification

- **Verification** is the confirmation, through the provision of objective evidence, that specified requirements have been fulfilled. (ISO/IEC/IEEE 15288)
- The scope of verification includes a set of activities that compares a system or system element against the requirements, architecture and design characteristics, and other properties to be verified (ISO/IEC/IEEE 2015).
- Verification is based on tangible evidence; i.e., it is based on information whose veracity can be demonstrated by factual results obtained from techniques such as inspection, measurement, testing, analysis, calculation, etc. Thus, the process of verifying a system consists of comparing the realized characteristics or properties of the product, service, or enterprise against its expected design properties.

Validation

- **Validation** is the confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.
- Validation is the set of activities that ensure and provide confidence that a system is able to accomplish its intended use, goals, and objectives (i.e., meet stakeholder requirements) in the intended operational environment (ISO 2005).
- To validate a system consists of demonstrating that it satisfies its system requirements and eventually the stakeholder's requirements. From a global standpoint, the purpose of validating a system is to acquire confidence in the system's ability to achieve its intended mission, or use, under specific operational conditions.

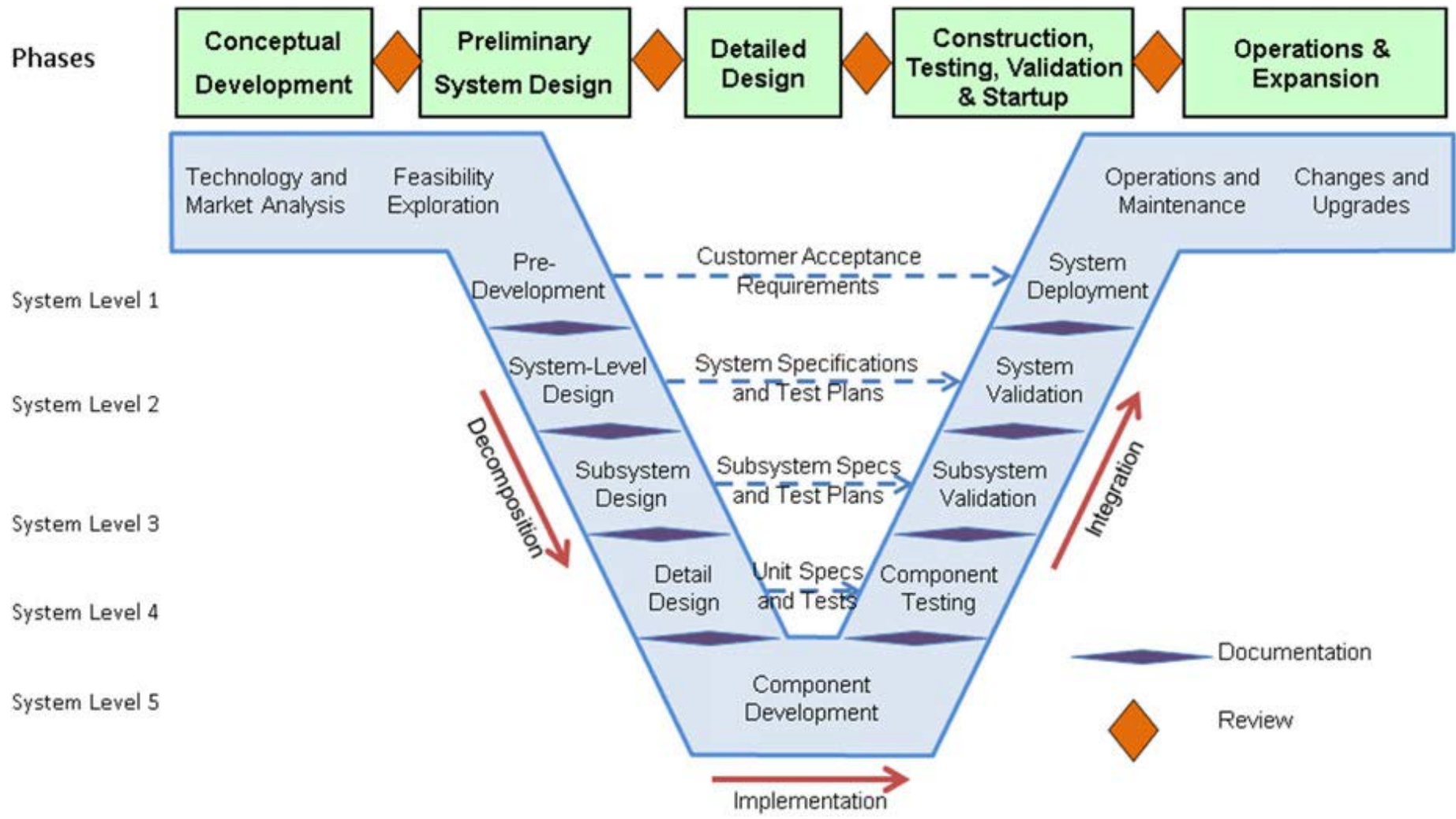
Verification vs. Validation

- Verification is always against the technical specifications and validation is always against the real world or the user needs.
- It is sometimes said that validation can be expressed by the query “Are you building the right thing?” and verification by “Are you building it right?”

The Systems Engineering “V” Model

- The “V” model represents the sequence of steps in a project life cycle development. It describes the activities to be performed and the results that have to be produced during product development.
- The left hand side of the “V”:
 - Represents the decomposition of requirements, and creation of system specifications.
 - Translates iteratively from “macro” to “micro” levels.
- The right hand side of the “V”:
 - Represents integration of parts and their validation.
 - Is a serial confirmation process moving from the part level up through the complete system/product.

The Systems Engineering “V” Model



Steven D. Eppinger, Nitin R. Joglekar, Alison Olechowski, Terence Teo, “Improving the systems engineering process with multilevel analysis of interactions”. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*. 2014, 28, 323-337.

Looking Ahead

- This lecture provided a brief introduction to some basic concepts related to systems engineering.
- We hope that the material that you learned will motivate you to learn more about systems engineering and systems thinking in the future.
- Try to use some of the concepts that you have learned when you are working on the design and development of products.

References: iBot

- <https://en.wikipedia.org/wiki/IBOT>
- <https://www.linkedin.com/pulse/dean-kamen-announces-reincarnation-ibot-wheelchair-paul-j-heney>
- http://www.nbcnews.com/id/30929301/ns/health-health_care/t/stair-climbing-wheelchair-comes-halt/
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