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System Engineering & Systems Thinking

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Contents

- What is a System?
- Systems engineering history
- What is system engineering?
- Evolution of “systems thinking”
- Key components of “systems thinking”
- Systems engineering process
- Role of systems engineer
- Ethical considerations
- Why system engineering?
- Systems engineering: a growing trend
- Summary

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What is a System?

- ***Definition of a System***
  (NASA Systems Engineering Handbook)

  – A system is a set of interrelated components which interact with one another in an organized fashion toward a common purpose.

- ***System components may be quite diverse***
  – Persons and Organizations
  – Software and Data
  – Equipment and Hardware
  – Facilities and Materials
  – Services and Techniques

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What is a System?

Table 1.2 Boulding's classification of systems (von Bertalanffy, 1968).

Level	Characteristics	Example
Structures	Static	Bridges
Clockworks	Predetermined motion	Solar system
Controls	Closed-loop control	Thermostat
Open	Self-maintaining	Biological cells
Lower organisms	Growth, reproduction	Plants
Animals	Brain, learning	Birds
Man	Knowledge, symbolism	Humans
Social	Communication, value	Families
Transcendental	Unknowable	God

- Categorizing systems is notoriously difficulty. Even providing examples may be fraught.
    - For instance, there are many systems engineers who deny that the solar system is a system at all, because a system has to be "manmade and purposeful"
- Boulding's classification has stood the test of time, and it certainly provides a basis for discussion and much head scratching

What is a System?

Open System Properties:

1. Importation of energy
2. The throughput (transforms energy that is available to them)
3. The output
4. Systems as cycles of events
5. Negative entropy (To survive, open systems must “ingest” negative entropy. This may come in the form of food, new staff, new organization, even new concepts and beliefs…)
6. Information input, negative feedback, and the coding/categorization process
7. The steady state and dynamic homeostatis. Importing energy to arrest increase in entropy can result in a steady-state condition, or quasi-stability, which may be dynamic in nature. Body temperature is a good example. Le Chatelier’s Principle can be seen in operation: changing any element within the open system causes other elements to rearrange themselves so as to oppose the change, and to restore the body as near to its previous state as possible.
8. Differentiation (open systems move in the direction of differentiation and elaboration)
9. Equifinality (open systems can reach the same final state from differing initial condition by a variety of paths (von Betalanffy proposed this principle but has not emerged as a universal truth yet))

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The Emergence Property

Emergence

Cartesian Reductionism could not explain why some wholes possess capabilities, have properties, and behave in ways that were not evident from examination of their parts in isolation. This observation was labeled 'emergence,' and some wholes were observed to possess or exhibit properties, capabilities and behaviors not exclusively attributable to any of their rationally separable parts.

It was evident, for example, that the human brain was made from many different neurons, each of which was of itself relatively simple, being able to adopt a very few discrete states. Yet, somehow, the combined effect of all these simple, interconnected, interactive neurons was to create self-awareness, which astonished — and still astonishes — any scientist who cared to think about it. How could that be?

There were many examples of this initially mysterious emergence, once people began to look. How could bringing together two odorless gases, nitrogen and hydrogen, result in ammonia, with its pungent odor? How could a film, made up as it was of a series of still frames, present apparent motion to a cinema audience?

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Systems Engineering

- ***Definition of Systems Engineering (NASA SE Handbook)***
  - Systems Engineering is a robust approach to the design, creation, and operation of systems.
- *Systems Engineering consists of*
  - Identification and quantification of system goals
  - Creation of alternative system design concepts
  - Performance of design trades
  - Selection and implementation of the best design (balanced and robust)
  - Verification that the design is actually built and properly integrated in accordance with specifications
  - Assessment of how well the system meets the goals

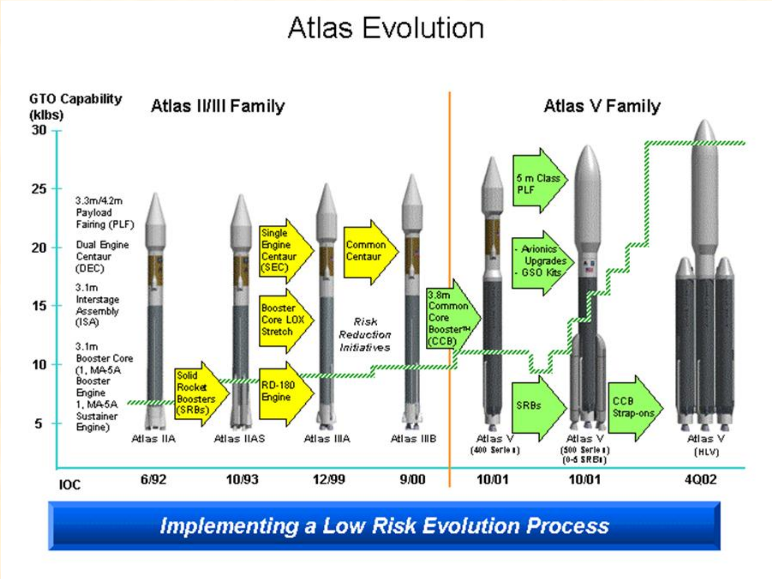
Systems Engineering History

- ***Water Distribution Systems in Mesopotamia 4000 BC***
- ***Irrigation Systems in Egypt 3300 BC***
- ***Urban Systems such as Athens, Greece 400 BC***
- ***Roman Highway Systems 300 BC***
- ***Water Transportation Systems like Erie Canal 1800s***
- ***Telephone Systems 1877***
- ***Electrical Power Distribution Systems 1880***

Modern Origins of the Systems Approach

- ***British Multi-disciplined Team Formed (1937)* to Analyze Air Defense System**
- ***Bell Labs* Supported Nike Development (1939-1945)**
- ***Semi-Automatic Ground Environment (SAGE)* Air Defense System Defined and Managed by MIT (1951-1980)**
- ***ATLAS Intercontinental Ballistic Missile Program* Managed by Systems Contractor, Ramo-Wooldridge Corp (1954-1964)**

Nike missile family on display at Redstone Arsenal, Alabama. From left, MIM-14 Nike Hercules, MIM-23 Hawk (front), MGM-29 Sergeant (back), LIM-49 Spartan, MGM-31 Pershing, MGM-18 Lacrosse, MIM-3 Nike Ajax



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Spread of the Systems Approach

- ***Early Proponents***
  - Research and Development Corporation (RAND)
  - Robert McNamara (Secretary of Defense under JFK)
  - Jay Forrester (founder of System Dynamics, which deals with the simulation of interactions between objects in dynamic systems. Modeling Urban Systems at MIT)
- ***Growth in Systems Engineering Citations (Engineering Index)***
  - Zero! in 1964
  - One Page in 1966
  - Eight Pages in 1969
- ***Nine Universities Offered Systems Engineering Programs in 1964***

1) Hughes, Thomas P., Rescuing Prometheus, Chapter 4, pps. 141-195, Pantheon Books, New York, 1998.

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A New Age: Systems Age

Table 1.1 Machine Age vs System Age paradigms (Ackoff, 1981).

Machine Age procedure	Systems Age procedure
■ Decompose that which is to be explained (decomposition) ■ Explain the behavior or properties of the contained parts separately ■ Aggregate these explanations into an explanation of the whole	■ Identify a containing system of which the thing to be explained is part ■ Explain the behavior or properties of the containing whole ■ Then explain the behavior of the thing to be explained in terms of its roles and functions within its containing whole.
Machine Age analysis	**Systems Age synthesis**
■ Analysis focuses on structure; it reveals how things work ■ Analysis yields knowledge ■ Analysis enables description ■ Analysis looks into things	■ Synthesis focuses on function; it reveals why things operate as they do ■ Synthesis yields understanding ■ Synthesis enables explanation ■ Synthesis looks out of things

A new age was declared: *the Systems Age*
In this bright new age, dynamic Systems Age thinking was compared with static Machine thinking (Ackoff, 1981)

What Is Systems Engineering (SE)?

Systems engineering

- An *interdisciplinary* field of engineering focusing on how complex engineering projects should be designed and managed over their *life cycles*.
- Deals with *work-processes* and tools to manage *risks* on such projects
- Addresses issues such as *logistics*, the coordination of different teams, and automatic control of machinery dealing with *large-scale* and *complex* projects.
- Overlaps with both *technical and human-centered* disciplines such as control engineering, industrial engineering, organizational studies, and project management.

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Evolution of Systems Thinking

- Since whole humans were whole systems too, it was possible to regard humans individually and in social groups and societies as exhibiting behavior
- Comparing human behavior with the 9 characteristics of an open system, *humans evidently exhibited additional characteristics*, which were the source of intense study
- ***Freud*** and ***Jung*** were foremost in this field. It also became evident with research that *"groups of humans" did not behave as individuals*. Jung, for example, observed:

> It is a notorious fact that the morality of society as a whole is in inverse ratio to its size; for, the greater the aggregation of individuals, the more the individual factors are blotted out, and with them morality, which rests entirely on the moral sense of the individual and the freedom necessary for this. Hence every man is, in a certain sense, unconsciously a worse man when he is in society than when acting alone, for he is carried by society and to that extent relieved of his individual responsibility. Any large company composed of wholly admirable persons has the morality and intelligence of an unwieldy, stupid and violent animal. The bigger the organization, the more unavoidable is its immorality and blind stupidity . . . the greatest infamy on the part of . . . a man's . . . group will not disturb him so long as his fellows steadfastly believe in the exalted morality of their social organization. (Jung, 1917)

- Both Freud and Jung might be described as early "***systems thinkers***": in their different ways they were trying to understand the whole human intellect and both saw the need to review the parts only in the context of the whole.
  - ***Developing systems theory*** encompassed, and incorporated, the ideas of *psychology*, *group psychology*, *social anthropology*, etc and deployed them into *organizational and management theory*, to address the behavior of ***whole*** social systems, of ***whole*** socioeconomic systems, and ***whole*** sociotechnical systems
  - (the last one was of particular importance, since organizations, businesses and industries were generally sociotechnical systems, with their people-content forming teams, groups, and divisions, and using machines which may also form social entities, such as distributed computer systems, sequential processing machines etc.)

Evolution of Systems Thinking

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Gestalt and Holism

Aristotle said:

> The whole is more than the sum of its parts.
> The part is more than the fraction of the whole.
>
> Composition Laws (Hall, 1989)

The world, it seemed, would not be ready for such a profound systems concept for a further 2000 years; not, that is until Gestalt – a German word with no clear English translation, but meaning something like 'form,' or 'shape.' The Gestalt movement started early in the twentieth century: Gestalt psychology was launched in 1912 by Max Wertheimer, who published a paper on the visual illusion of movement created by presenting a series of still photographs of a galloping horse. The central tenet of Gestalt thinking was that the whole was greater than the sum of the parts.

A more current view might be that a Gestalt entity is a physical, biological, psychological, or symbolic configuration or pattern of elements, so unified as a whole that its properties cannot be derived from a simple summation of its parts. From this perspective, the whole is different from, not necessarily greater than, the sum of the parts. . . .

The Gestalt notion is contained within contemporary ideas of holism:

- Holism: the theory that the fundamental principle of the universe is the creation of wholes, i.e., complete and self-contained systems from the atom and the cell by evolution to the most complex forms of life and mind;
- Holism: the theory that a complex entity, system, etc., is more than merely the sum of its parts (*Chambers Dictionary*).

Gestalt has left a legacy, often overlooked, but nonetheless deeply embedded in today's systems thinking. Contemporary systems engineering, for instance, seems to owe more in practice to Gestalt than to operations research, since ideas of holism and emergence are firmly embedded, whereas mathematical optimization might be proposed by academics, but seems to be of little interest to engineers. Without optimization, however, requisite emergent properties may not be fully exhibited . . . .

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Systems Thinking

- ***Systems thinking is thinking***, *scientifically*, about phenomena, events, situations, etc., from a systems perspective, i.e., using *systems methods*, *systems theory* and **systems tools**. ***Systems thinking, then, looks at wholes, and at parts of the wholes in the context of their respective whole***. It looks at wholes as ***open systems***, interacting with other systems in their environment. Instead of thinking in the abstract sense, systems thinking has developed into ***dynamic modeling of open systems***, often using smart simulation programs

- ***Because systems ideas are applicable to all kinds of systems***, and are hence not limited by particular physical/structural/procedural constraints, systems thinking has evolved as modeling, particularly, the ***behavior*** of systems. This offers the opportunity to take maximum advantage of behavioral isomorphs. It also afford the ***ability to manage complexity***, so that highly complex phenomena, situations, organizations, etc. may be modeled with some degree of confidence

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- Like any form of computer simulation, ***behavior modeling in not infallible***. This issue is alleviated, in some degree, by ***the way in which behavior modeling and systems thinking are used***.
  - In general, these methods are not used to provide specific numerical answers to complex mathematical problems. Instead, they are used to *model the interactions between various systems-of-interest* to explore likely outcomes from such interaction in some future environment.
  - The models assume too, that each system and its interactions affect other systems in the model and surrounding the model, so that the whole are used as experimental laboratories, to explore what might happen in some future situation, to explore the "what ifs"… to see if there are likely to be any counterintuitive effects from unexpected interactions

- Systems thinking has been fuelled and enabled by the development of ***systems dynamics tools***, of which there are many now available o the market. One such is STELLA, which stands for: ***Systems Thinking and Experimental Learning Laboratory Approach***: the title typifies the approach.

Key Components of Systems Thinking

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1. *Holism*. A system is a whole. An open system is a whole. The whole is different from, and may be greater than, the sum of its rationally separable parts.
2. *Organicism*. A whole (system) may be an organism, or may be analogous to an organism, in that the many interacting parts behave as a unified whole. The rationally separable parts exist in virtual symbiosis, each depending upon, and being defined by, the sum of the other interacting parts
3. *Synthesis*. It is possible to form a whole from open, interacting parts such that the whole may exhibit desired, or requisite, emergent properties, capabilities and behaviors. This is a functionalist viewpoint, or *Weltanschauung*, and is the *raison d'être* of systems engineering
4. *Variety*. The parts of a subsystem are complementary: they cooperate and coordinate their various actions. The parts are therefore mutually different, i.e., they exhibit variety, and so too must their interactions and interconnections to complement each other. There is a minimum variety of parts for any system to exist and continue to exist.
5. *Emergence*. Emergent properties, capabilities and behaviors derive from interactions between the parts, and are traceable therefore principally to coupled processes, rather than to structure. Emergence arises only when the parts of a whole interact, or conversely when the coupled processes flowing through the system are active. An open system, therefore, is only a whole while it is both complete and internally dynamic.

Key Components of Systems Thinking

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6. *System*. A system is an open set of complementary interacting parts, with properties, capabilities and behaviors emerging, both from the parts and from their interactions, to synthesize a unified whole. The definition encompasses the first five precepts: holism, organicism, synthesis, variety and emergence.
7. *Homeostasis*. Stability in open systems occurs at high, rather than low, energy. Stability is a dynamic steady state, brought about when inflows balance outflows. Homeostasis is necessary in a variety of parameters in complex systems, including energy, resources, waste, material inflow, product outflows, and many, many more.
8. *Viability*. The viability of open systems depends in part on achieving and maintaining homeostasis, but also on their ability to neutralize threats from without and within, to adapt and change with circumstance, and to maintain synergy — cooperation and coordination between the parts, to act as a unified whole in achieving some desired external effect.
9. *Purpose*. Manmade systems are viewed as having purpose, one perhaps that they were designed to achieve, or one that they have adopted. It is 'helpful' to consider the human element of systems as having purpose, or intent, and to consider the technological/artifact element of systems as serving that human purpose. So, the parts within a whole may be purposive, i.e., an observer might attribute purpose to them. The parts contribute to the objectives and purpose of the whole, but the purpose of the parts need not aggregate to the purpose of the whole.

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Key Components of Systems Thinking

0. *Behavior.* Open systems exhibit behavior, i.e., they respond to stimulus. Since open systems are interconnected and interact with other open systems, they are constantly stimulated and exhibiting behavior. Where the behavior of a system is consistent and predictable, the system may be usefully described by its behavior, so diminishing the need to describe the internals of the system; this is a direct means of reducing perceived complexity. Intelligence is marked by the ability of a system to change its behavior according to situation, e.g., it may not respond to the same stimulus in the same way every time, as would a machine or a simple organism.

1. *Isomorphs.* Different systems may exhibit the same behavior, i.e., they respond identically to the same stimulus, although they may be comprised of different parts. Clearly true of many physical systems, it may also be true of some natural systems at some times.

2. *Ideals — the Ideal System.* A concept exists in systems thinking and in systems engineering of the ideal system: it is the best that planners and designers can conceptualize (Hall, 1989). The ideal system can become a yardstick against which to compare options and alternatives, or against which to measure that which is realized.

3. *Values.* Value in artificial systems is often related to utility; the more useful a system, the more it is valued. The value of a subsystem or part of a whole may be judged in the degree with which it contributes to its containing system's objectives in concert with the other subsystems and parts. The value of a subsystem or part may also be judged by the degree in which it complements the other subsystems, particularly where, without such complementation, the other subsystems and the whole would not exist.

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Systems Thinking

We see that the ***solar system*** is indeed a system, ***organisms*** are systems, a ***complete set of ideas*** can be a system, a series of ***strategically placed stepping stones a river*** can be a system. We can also see that it is possible to create artificial, or human activity systems in which the whole is greater than the sum of the parts, which has important implications:

- Systems can be created that *exceed the capability implicit in their technology , or implicit in the sum capabilities of individuals, or both*
- Systems can be created that proffer ***greater value than the sum cost of their parts*** would indicate
- Systems can be created that *may proffer the desired value at less than the sum cost of their separate parts would indicate*

Not everything is a system, however, since not everything is a whole. For example, a fighter aircraft without the crew is not a whole. Similarly, software without processor is not a whole, simply a set of instructions; a computer without its software is similarly not a whole, simple a machine without instructions. A marriage is not a whole, by definition, unless it joins together complementary man and woman into a single union

Building Blocks of Systems Engineering

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- ***Math & Physical Sciences***
  - Qualitative modeling
  - Quantitative modeling
  - Physical modeling
  - Theory of Constraints
  - Physical Laws
- ***Management Sciences***
  - Economics
  - Organizational Design
  - Business Decision Analysis
  - Operations Research
- ***Social Sciences***
  - Multi-disciplinary Teamwork
  - Organizational Behavior
  - Leadership
- ***Body of Knowledge***
  - Problem definition
    - Concept of operations
    - System boundaries
    - Objectives hierarchy
    - Originating requirements
  - Concurrent engineering
    - System life cycle phases
    - Integration/Qualification
  - Architectures
    - Functional/Logical
    - Physical/Operational
    - Interface
  - Trades
    - Concept-level
    - Risk management
    - Key performance parameters

Unique to Systems Engineering

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Systems Engineering & Component Engineering

- **Science**

Determines what Is

- **Component Engineering**

Determines what Can Be

- **Systems Engineering**

Determines what Should Be

Systems Engineering Contributions

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- ***Systems engineering brings two elements to a project that are not usually present***
  - A disciplined focus on the
    - *end product,*
    - *its enabling products, and*
    - *its internal and external operational environment (i.e., a **System View**)*
  - A consistent vision of stakeholders' expectations independent of daily project demands (i.e., the ***System's Purpose***)

Ethical Considerations

- ***Achieving balance between inherent conflicts***
  - System Functionality and Performance
  - Development Cost and Recurring Cost
  - Development Schedule (Time to Market)
  - Development Risk (Probability of Success)
  - Business Viability and Success
- ***System Optimization***
  - Subsystems often suboptimal to achieve best balance at system level
  - Ultimate system purpose must prevail against conflicting considerations
  - Long-term considerations (e.g., disposal) may drive technical decisions
- ***Customer Interface***
  - Often must act as "honest broker"
  - Carries burden of educating customer on hard choices
  - Must think ahead to the next customer and next application
  - Must "challenge" all requirements

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Two Perspectives on SE

- ***SE is a way of thinking***
  - Practiced by senior engineers
  - Is unique to the product/industry of the engineering firm
  - Should be taught within other engineering disciplines
  - Scientific foundations and body of knowledge have commonality across product/industry but are not unique to SE
  - SE team has engineers of all disciplines

- ***SE is a discipline of engineering***
  - Has scientific foundations that cross many other engineering disciplines
  - Has body of knowledge separate from other disciplines
  - Can be taught separately from other disciplines in an engineering school
  - Separate roles exist on the SE team for a specific product

time →

SE as an Engineering Discipline

- ***Scientific Foundations***
  - Qualitative modeling
    - Data modeling
    - Process modeling
  - Quantitative modeling
    - Behavioral modeling
    - Feedback and control
    - "ility" modeling
    - Trade-off modeling
  - Physical modeling
    - Prototypes for requirements
    - Usability testing
    - Prototypes for interface resolution
    - Integration/qualification

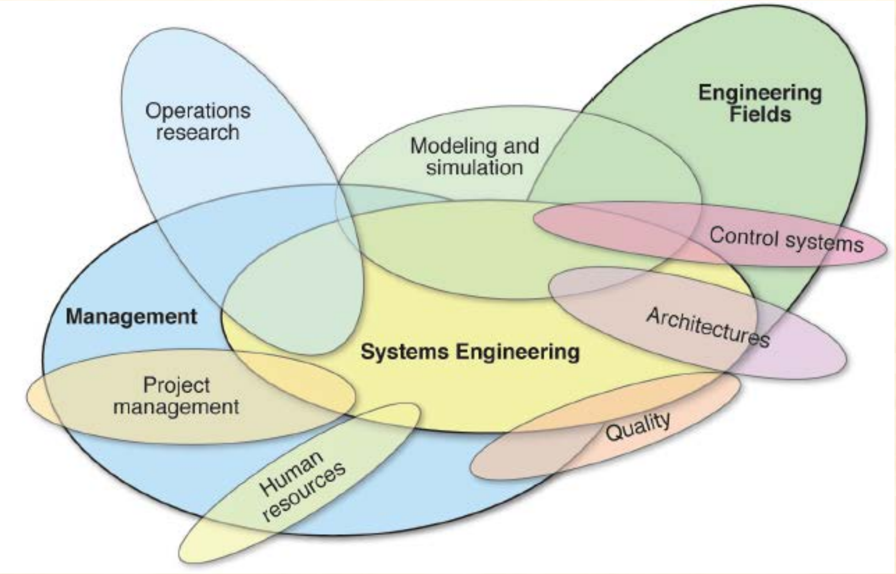
- ***Body of Knowledge***
  - Problem definition
    - Concept of operations
    - System boundaries
    - Objectives hierarchy
    - Originating requirements
  - Concurrent engineering
    - System life cycle phases
    - Integration/Qualification
  - Architectures
    - Functional/Logical
    - Physical/Operational
    - Interface
  - Trades
    - Concept-level
    - Risk management
    - Key performance parameters

Systems Engineering: A Growing Trend

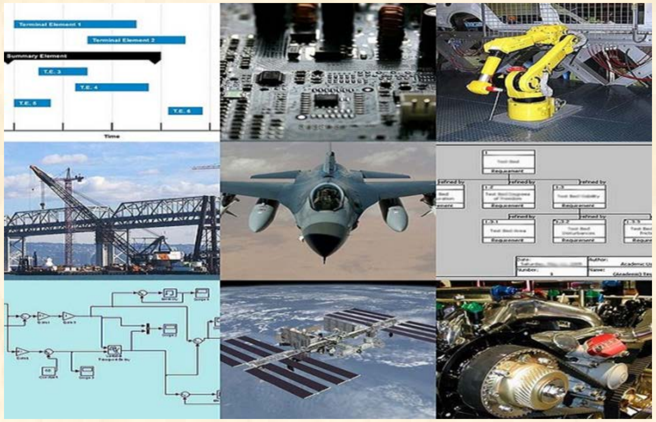
Council of Engineering Systems Universities (CESUN), established in 2005, survey of its members:

- In addition to research in more traditional engineering departments (energy, environment, transportation, defense, etc) universities were involved in projects related to health care and homeland security, as well as research in the management of innovation, megacities, and financial systems.

- *This indicates emergence of Systems Engineering in new areas (health care delivery) where engineering has not traditionally been applied*



Interfaces of systems engineering to other fields



System Engineering is Applied Everywhere

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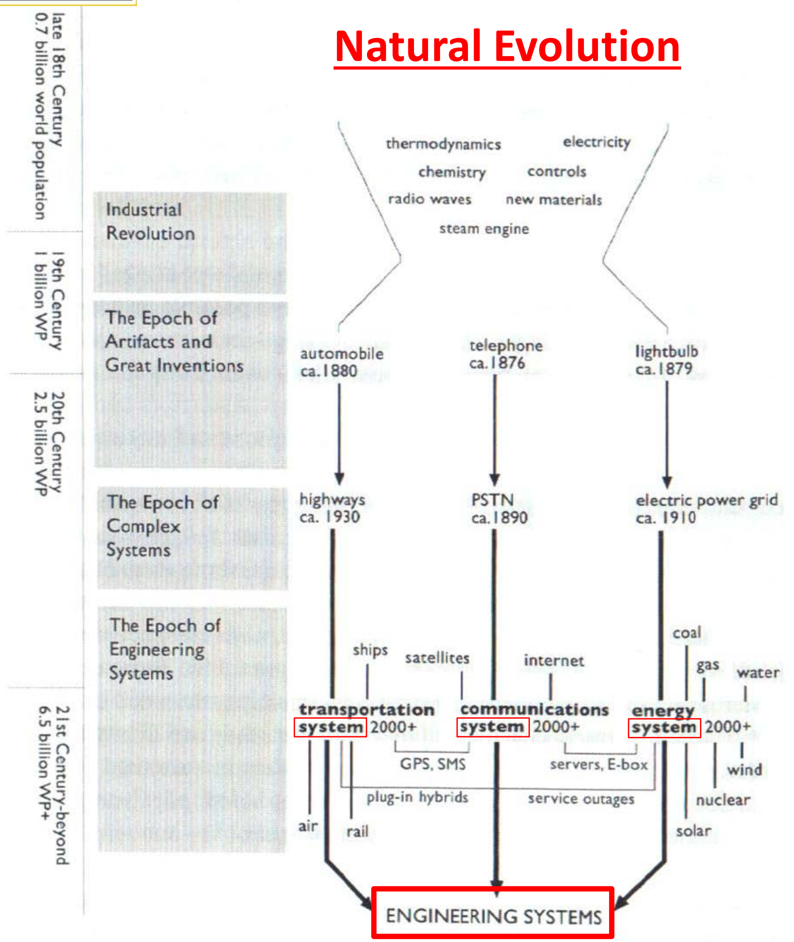
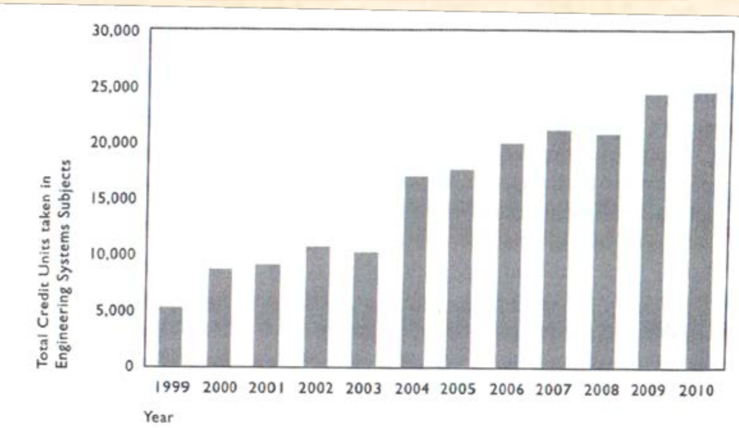
Why System Engineering?

Natural Evolution and Growing Market Demand



Major epochs in the evolution towards engineering systems.
Source: de Weck et al., 2011.



Total number of credits taken by MIT students in engineering systems subjects (1999-2010). *Source: MIT Office of the Provost*

- At MIT, the number of credit units taken by students in system engineering subjects has more than quadrupled over the last decade

- "Out in the real (i.e., nonacademic) world, these students have learned, sometimes in frustrating ways, that a narrow view of technology is inadequate for solving large societal problems and that successful solutions must include a coordinated mix of technical innovations, organizational strategies, and carefully crafted policies", *de Weck et al. at MIT*

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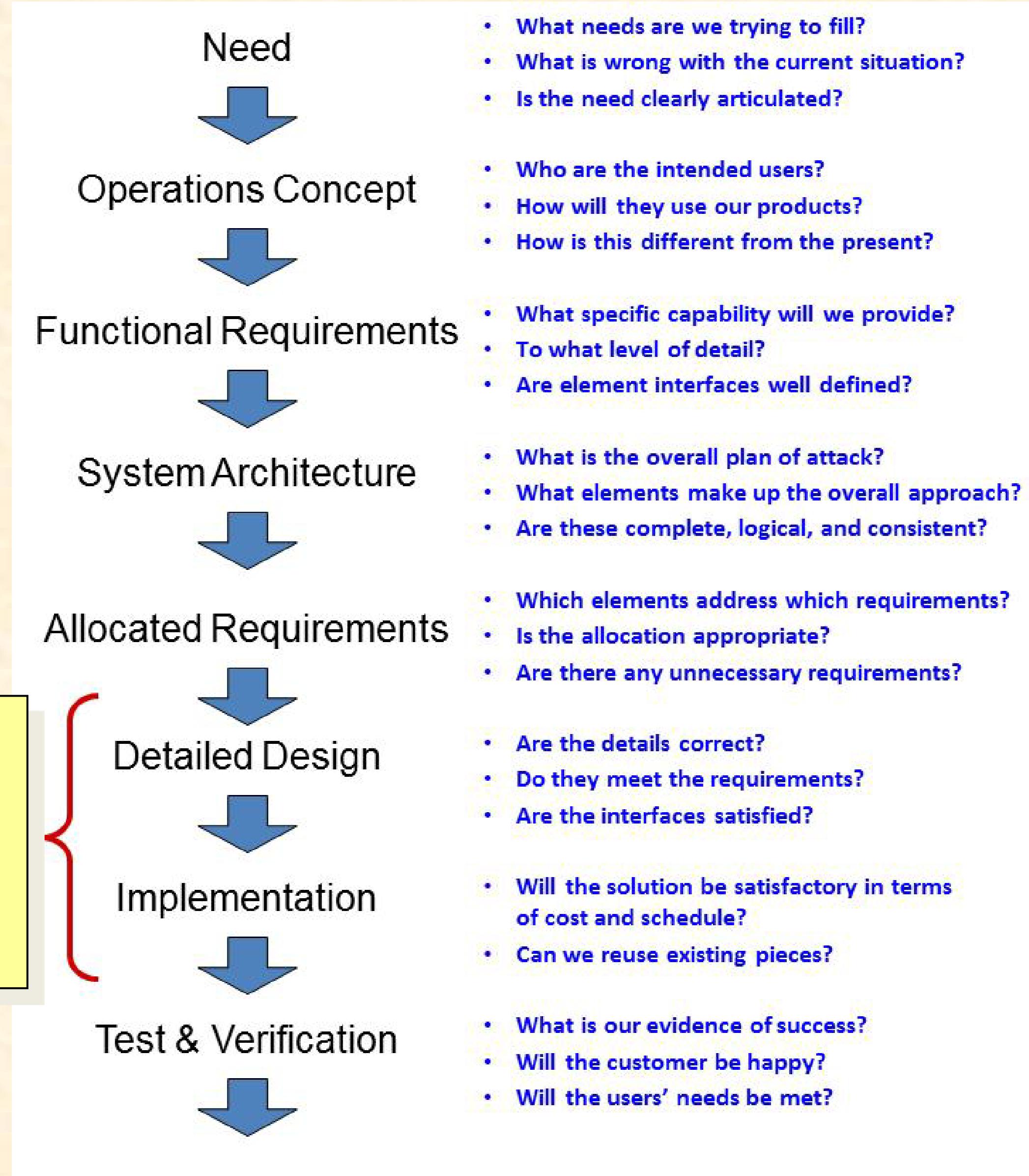
Systems Engineering Process at a Glance

- Focus of Systems Engineering
  - From Original Need
  - To Final Product
    - The Whole System
    - The Full System Life Cycle



- Focus of Component Engineering
  - On Detailed Design
  - And Implementation

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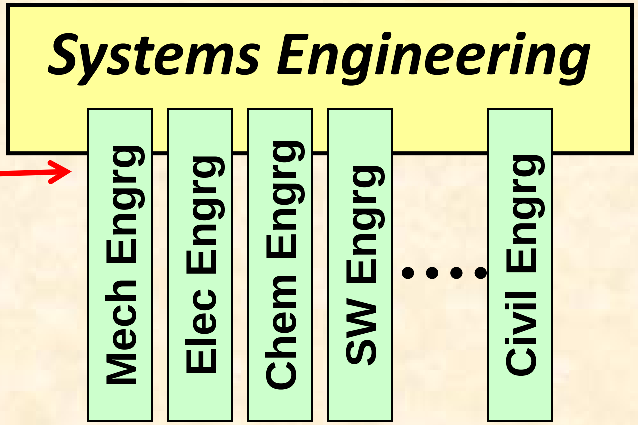
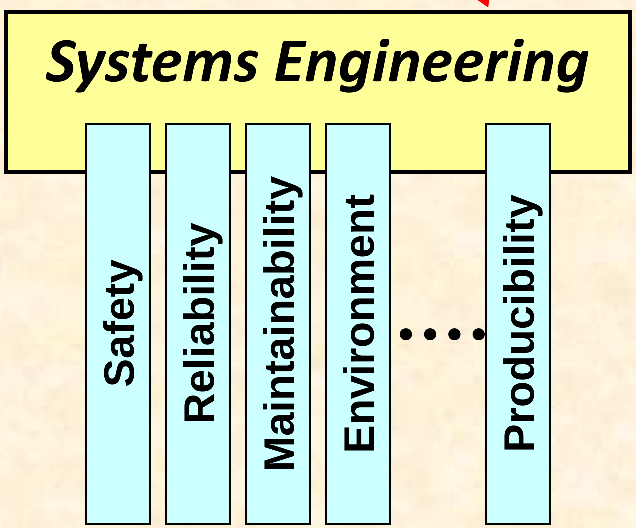
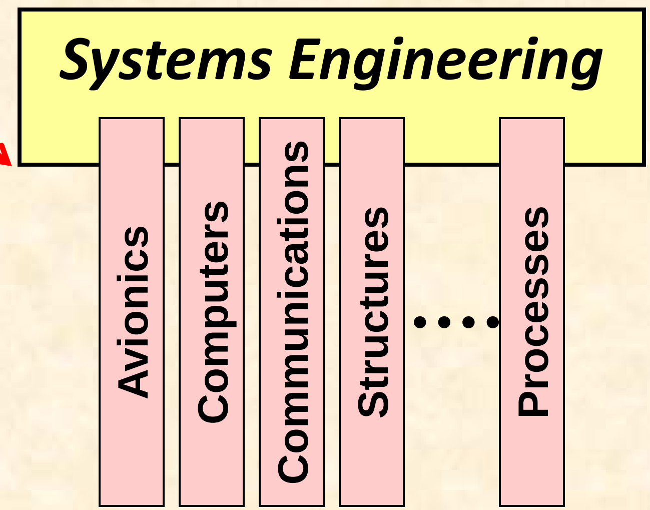
Role of Systems Engineering in Product Development

- Integrates Technical Effort Across the Development Project
  - Functional Disciplines
  - Technology Domains
  - Specialty Concerns







- Focus of Systems Engineering
  - From Original Need
  - To Final Product
    - The Whole System
    - The Full System Life Cycle

- Focus of Component Engineering
  - On Detailed Design
  - And Implementation

Need

- What needs are we trying to fill?
- What is wrong with the current situation?
- Is the need clearly articulated?

Operations Concept

- Who are the intended users?
- How will they use our products?
- How is this different from the present?

Functional Requirements

- What specific capability will we provide?
- To what level of detail?
- Are element interfaces well defined?

System Architecture

- What is the overall plan of attack?
- What elements make up the overall approach?
- Are these complete, logical, and consistent?

Allocated Requirements

- Which elements address which requirements?
- Is the allocation appropriate?
- Are there any unnecessary requirements?

Detailed Design

- Are the details correct?
- Do they meet the requirements?
- Are the interfaces satisfied?

Implementation

- Will the solution be satisfactory in terms of cost and schedule?
- Can we reuse existing pieces?

Test & Verification

- What is our evidence of success?
- Will the customer be happy?
- Will the users' needs be met?

The Systems Engineering Approach

The systems approach was seen as a way of addressing complex problems and issues. Ackoff (1981) suggested that there were three ways in which problems could be addressed:

1. Problems could be *resolved*. To resolve a problem is to find an answer that is 'good enough,' one which satisfices.
2. Problems could be *dissolved*. To dissolve a problem is to change the situation in some way such that the problem disappears, to 'move the goalposts.'
3. Problems could be *solved*. To solve a problem is find the correct answer, as in solving an equation.

Resolve: In general, most people resolved problems. Often by dealing more with the symptoms than by getting to the roots of the problem: sometimes they has to make decision in absence of full knowledge. Satisficing was not seen as bad, more pragmatic. Sometimes satisficing resulted in more knowledge about the real problem, enabling further satisficing and more knowledge, so homing in on a complete solution to a problem.

Dissolve: Some people, however, were good at dissolving problems. Making them go away. Politicians are often thought of a working in this way, and it can prove smarter, less confrontational and less expensive than other methods. However, it also can come at a delayed or hidden cost, as when the UK attempted to appease Hitler before World War II. Appeasement, in that context, was an attempt to move the goalposts, and it did not work.

A third way: some systems engineers chose the third route– they sought the "***best solution***", the "***optimum***", to a complex problem by so balancing the interacting components and coupled processes of a complex solution system that it gave the ***best results in its environment***. This was a management task and, potentially at least, a mathematical task… as well as requiring ***understanding of just how emergent properties, capabilities and behaviors could be synthesized and realized***

Satisficing: decide on and pursue a course of action satisfying the minimum requirements to achieve a goal

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Summary

- ***Systems Engineering***
  - Has Unique Focus
    - End product and system purpose
    - Stakeholder needs and expectations
    - Full system life cycle
      (Conception through Retirement)
  - Has Unique Approach
    - Integrates disciplines and technologies
    - Balances conflicting considerations
  - Has Unique Methods, Tools & Models for
    - System analysis and simulation
    - Assessment of performance and risk
    - Organization and management of
      information and requirements
    - Verification and validation