National Aeronautics and Space Administration

Engineering Elegant Systems: Systems Engineering Postulates, Principles, and Hypotheses Related to Systems Principles

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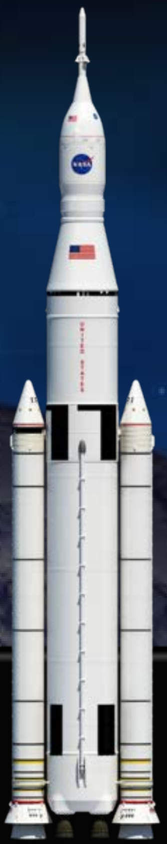


Space Launch System

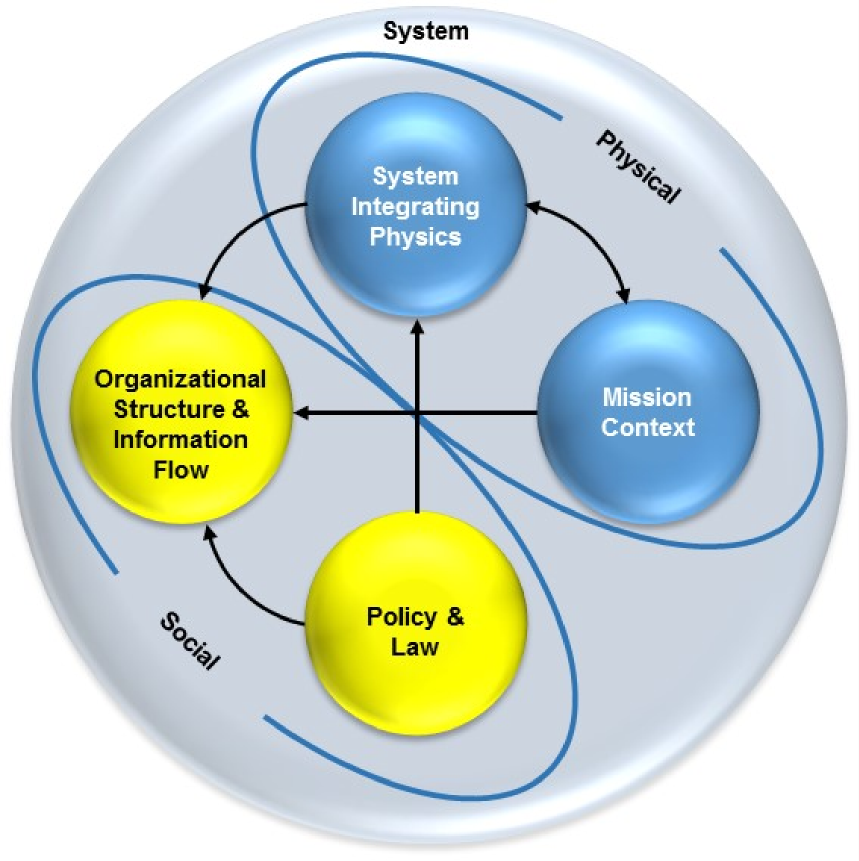
Systems Engineering Principles and System Principles

- **What is the relationship between Systems Engineering Principles and System Principles?**
  - Systems Engineering Principles – Principles guiding the engineering of a system
  - System Principles – Principles which define the characteristics of a physical and/or logical system
  - Organizational Principles – Principle which define the structure and functioning of an organization
- **Systems Engineering Principles encompass**
  - System Principles of the specific system being engineered
  - Sociological aspects of the organization engineering the system
- **System Engineering Principles guide application of Systems Engineering Processes**
- **System Principles encompass the system type:**
  - Physical
    - Thermodynamic (e.g., aeronautic, automobiles, electrical, nautical, rockets)
    - Optical (e.g., telescopes)
    - Biological (e.g., human, animal, plant, natural systems)
    - Structural (e.g., bridges, buildings, towers)
  - Logical (e.g., data, software)
  - Social (e.g., internet social media, gaming)
  - System of systems are the integration of multiple systems of the same or different type

Understanding Systems Engineering

- **Definition – System Engineering is the engineering discipline which integrates the system functions, system environment, and the engineering disciplines necessary to produce and/or operate an elegant system.**
  - Elegant System - A system that is robust in application, fully meeting specified and adumbrated intent, is well structured, and is graceful in operation.

- **Primary Focus**
  - System Design and Integration
    - Identify system couplings and interactions
    - Identify system uncertainties and sensitivities
    - Identify emergent properties
    - Manage the effectiveness of the system
  - Engineering Discipline Integration
    - Manage flow of information for system development and/or operations
    - Maintain system activities within budget and schedule



- **Supporting Activities**
  - Process application and execution

Systems Engineering Postulates

System Integration (physical/logical system)
Discipline Integration (social system)
Both System and Discipline Integration

- **Postulate 1: Systems engineering is system specific and context dependent**
- **Postulate 2: The Systems Engineering domain consists of subsystems, their interactions among themselves, and their interactions with the system environment**
- **Postulate 3: The function of Systems Engineering is to integrate engineering disciplines in an elegant manner**
- **Postulate 4: Systems engineering influences and is influenced by organizational structure and culture**
- **Postulate 5: Systems engineering influences and is influenced by budget, schedule, policy, and law**
- **Postulate 6: Systems engineering spans the entire system life-cycle**
- **Postulate 7: Understanding of the system evolves as the system development or operation progresses**
- **Postulate 7 Corollary: Understanding of the system degrades during operations if system understanding is not maintained.**

Systems Engineering Principles

- **Principle 1: Systems engineering integrates the system and the disciplines considering the budget and schedule constraints**
- **Principle 2: Complex Systems build Complex Systems**
- **Principle 3: The focus of systems engineering during the development phase is a progressively deeper understanding of the interactions, sensitivities, and behaviors of the system**
  - Sub-Principle 3(a): Requirements and models reflect the understanding of the system
  - Sub-Principle 3(b): Requirements are specific, agreed to preferences by the developing organization
  - Sub-Principle 3(c): Requirements and design are progressively defined as the development progresses
  - Sub-Principle 3(d): Hierarchical structures are not sufficient to fully model system interactions and couplings
  - Sub-Principle 3(e): A Product Breakdown Structure (PBS) provides a structure to integrate cost and schedule with system functions
- **Principle 4: Systems engineering has a critical role through the entire system life-cycle**
  - Sub-Principle 4(a): Systems engineering obtains an understanding of the system
  - Sub-Principle 4(b): Systems engineering models the system
  - Sub-Principle 4(c): Systems engineering designs and analyzes the system
  - Sub-Principle 4(d): Systems engineering tests the system
  - Sub-Principle 4(e): Systems engineering has an essential role in the assembly and manufacturing of the system
  - Sub-Principle 4(f): Systems engineering has an essential role during operations and decommissioning

Systems Engineering Principles

- **Principle 5: Systems engineering is based on a middle range set of theories**
  - Sub-Principle 5(a): Systems engineering has a physical/logical basis specific to the system
  - Sub-Principle 5(b): Systems engineering has a mathematical basis
    - Systems Theory Basis
    - Decision & Value Theory Basis (Decision Theory and Value Modeling Theory)
    - Model Basis
    - State Basis (System State Variables)
    - Goal Basis (Value Modeling Theory)
    - Control Basis (Control Theory)
    - Knowledge Basis (Information Theory)
    - Predictive Basis (Statistics and Probability)
  - Sub-Principle 5(c): Systems engineering has a sociological basis specific to the organization

- **Principle 6: Systems engineering maps and manages the discipline interactions within the organization**

- **Principle 7: Decision quality depends on the coverage of the system knowledge present in the decision-making process**

- **Principle 8: Both Policy and Law must be properly understood to not overly constrain or under constrain the system implementation**

- **Principle 9: Systems engineering decisions are made under uncertainty accounting for risk**

Systems Engineering Principles

- **Principle 10: Verification is a demonstrated understanding of all the system functions and interactions in the operational environment**
  - Ideally requirements are level and balanced in their representation of system functions and interactions
  - In practice requirements are not balanced in their representation of system functions and interactions

- **Principle 11: Validation is a demonstrated understanding of the system's value to the system stakeholders**

- **Principle 12: Systems engineering solutions are constrained based on the decision timeframe for the system need**

System Engineering Hypotheses

- **Hypothesis 1: If a solution exists for a specific context, then there exists at least one ideal Systems Engineering solution for that specific context**
  - Hamilton's Principle shows this for a physical system
    - $\int_{t_1}^{t_2}(\delta T - \delta V + \delta W)dt = 0$
- **Hypothesis 2: System complexity is greater than or equal to the ideal system complexity necessary to fulfill all system outputs**
- **Hypothesis 3: Key Stakeholders preferences can be accurately represented mathematically**
- **Hypothesis 4: The real physical system is the perfect model of the system**
  - Kullback-Liebler Information shows the actual system is the ideal information representation of the system
    - $I(f,g) = \int f(x)\log(f(x))\,dx - \int f(x)\log(g(x|\theta))\,dx = 0$

Systems Engineering Principles related to System Principles and Organizational Principles

- Postulate 1: Systems Engineering is product and environment specific, and context dependent.
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  - Sub-Principle 5(b): Systems engineering has a physical/logical basis
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- Katina, P. F. (2016). Systems Theory as a Foundation for Discovery of Pathologies for Complex System Problem Formulation. In Applications of Systems Thinking and Soft Operations Research in Managing Complexity (pp. 227–267). Cham: Springer.
  - Complementary - Two different perspectives or models about a system will reveal the truths regarding the system that are neigher entirely independent nor entirely compatible.
  - Control - The process by means of which a whole entity retains its identity and/or performance under changing circumstances.
  - Darkness - Each element in the system is isgnorant of the behavior of the system as a whole, it responds only to information that is available to it locally. This point is vitally important. If each element "knew" what was happening to the system as a whole, all of the complexity would have to be present in that element.
  - Dynamic Equilibrium - For a system to be in a state of equilibrium, all subsystems must be in equilibrium. All subsystems being in a state of equilibrium, the system must be in equilibirum.
  - Emergence - Whole entities exhibit properties which are meaningful only when attributed to the whole, not its parts - e.g., the smell of ammonia. Every model of systems exhibits properties as a whole entity which derive from its component activities and their structure, but cannot be reduced to them.
  - Equifinality - If a steady state is reached in an open system, it is independent of the initial condictions, and determined only by the system parameters, i.e., rates of reaction and
- System Pathologies Laws, Principles, and Theorems of Complex Systems
  - Principle of minimal critical specification - There are two aspects of this principle, positive and negative. The positive aspect ofthe principle suggests a need for identifying what is essential for design while the negative aspect suggests that no more should bespecified than is absolutely essential for design of complex systems"
  - Theorem of morphogenesis - The ability of complex systems to maintain stability in the context of change conditioned by a morphocatalysis (i.e., conditioned by system contact or co-presence of another system). System-enhancing behavior such as growth, creativity, innovation and change are allowed to remain functional based on other systems. However, it also connotes change in the context of stability inasmuch as stability is required in order for the system to be able to change and to maintain itself in the face of external change
  - Principle of multifinality - This principle suggests that complexorganizations with similar histories and conditions can have outcomes that vary widely. Thus, we can't draw premature conclusions regarding outcome expectations for different organizations that appear to be operating under similar conditions"
  - Principle of omnivory - This principle suggests that stability in acomplex system is achieved by having a greater number of different resources and of pathways for their flow to the main system components (i.e., modification of internal structures to enable intake of different inputs [resources]. In other words: spread the risks or 'don't put all your eggs in one basket'."
  - Principle of Pareto - In any large complex system, it appears thateighty percent of the outputs or objectives will be produced by only twenty percent of the system means. For example, the case whereeighty percent of the shares are held by twenty percent of the shareholders or twenty percent of the sizes (coats, trousers, and shoes) fit eighty percent of the customers"
  - Theory of punctuated equilibrium - The theory suggests that most systems exhibit little net evolutionary change for most of their geological history, remaining in an extended state of stasis (i.e., a period or state of inactivity or equilibrium). However, when such a significant evolutionary change occurs in such systems, it is generally restricted to rare and rapid change that occurs, on a geologic time scale, through a process of cladogenesis (i.e., the process by which a species splits into two distinct species rather than one species gradually transforming into another)
  - Theorem of purposive behaviorism ... behavior, performance, ... 'intended' purpose or ...
  - Theorem of recursive s... organizational structure and structure at one lev...
  - "Principle of redundanc... potential to act effective... resides"
  - Principle of redundancy ... goals requires redundan... accessed as backup or ...
  - Principle of relaxation ti... the mean time interval ...
  - Law of requisite salienc... awaiting discovery in ea...
  - Principle of resilience - ... characterized by defens... warning systems, or cri...
  - Law of requisite hierarc... needed in the organizat...
  - Principle of least effort ... adapting to its environm...
- System Pathologies Laws, Principles, and Theorems of Complex Systems
  - Law of requisite parsimony - Human short-term brain activity (memory) is incapable of dealing or recalling more than seven plus or minus two items
  - Law of requisite variety - The control achieved by a given regulatorysub-system over a given system is limited by: (1) the variety of the regulator and (2) the channel capacity between the regulator and thesystem
  - Theory of system boundary - Every system has a set of boundaries thatindicates some degree of differentiation between what is included and excluded in the system. Boundary is critical since, too narrow or too broad a boundary gives a false impression of the system of interest—resulting in pursuit of solutions to the wrong 'system'problem. Boundary identification is necessary to have a minimum description required to distinguish a system from its environment"
  - Theory of system environment - This theory is the basis for suggesting that every system operates in an environment which is always outside the control of the system and yet it (the environment) can influence system processes and behavior. Moreover, since systems do not control the environment, they can only adapt to changes in the environment
  - Principle of buffering - Stability of systems is enhanced by maintaining a surplus. However, an unused reserve cannot help the system. Whether we are talking about petroleum or wheat reserves or excess capacity to store food or water in the body, the surplus serves to buffer the system against an unexpected increase in demand
  - Principle of self-organization - Complex systems organize themselves lacking outside intervention; they exhibit emergentglobal structure and behavior out of interactions of local and seeminglyindependent components [systems, elements or parts]
  - Theory of sociotechnical systems - At the core of this theory is the notion that the design and performance of complex systems can be improved, and indeed can only work satisfactorily, if the 'social' and the 'technical' are brought together and treated as interdependent aspects of a work system. This 'joint optimization' of the technical and social subsystems, that constitute a total work system with neither subsystem being superior to another, is necessary for successful design and operation of a complex sociotechnical system
  - Principle of sub-optimization - If each subsystem, regarded separately, is made to operate with maximum efficiency, the system as a whole will not operate with utmost efficiency. More critically, independent improvement of a particular subsystem may actually worsen the overall performance of the whole
  - Principle of transcendence - Complex systems seem to organize and radiate information in other dimensions beyond physical space-time and mental boundaries of learning, development, and evolution. In such instances material structures are no longer considered the primary reality. God is seen as the source of all being and particularly as the source of evolutionary force, exemplified by that which 'transcends' our capability to fully comprehend, existing beyond scientific explanation
  - Principle of satisfying - This is the decision-making process wherebyone chooses an option that is, while perhaps not the best, good enough. In essence, satisfying is attaining a certain minimumquality level for the decision, enough to solve the problem but not necessarily more"
  - Principle of basins of stability - Complex systems have basins of stability which are separated by the thresholds of instability or phases of transition. When acted upon, systems will tend to move into another state (basin) of stability. Thus, a system 'parked' on a ridge will 'roll downhill'
  - Principle of viability - To maintain viability, there must be effectiveorganizational balance maintained along two dimensions: (1) Autonomy of organizational units verses integration of the system as awhole and (2) Stability of operations versus adaptation to changing conditions"

- **P. Senge (1990), The Fifth Discipline (pp. 57–67); reprinted in B. Lawson (2010), A Journey Through the Systems Landscape (p. 70).**
  - 1. Today's problems come from yesterday's solutions.
  - 2. The harder you push, the harder the system pushes back.
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  - 6. Faster is slower.D7. Cause and effect are not closely related in time and space.
  - 7. Cause and effect are not closely related in time and space.
  - 8. Small changes can produce big results—but the areas of highest leverage are often the least obvious.
  - 9. You can have your cake and eat it too—but not at once.
  - 10. Dividing an elephant in half does not produce two small elephants.
  - 11. There is no blame.

System Principles Questions

- **System Principles in current literature are a compilation of variance physical concepts applied at a full system level**
  - Interactions between these system principles is not yet well defined
    - Are there dependencies? (i.e., interactions among principles)
    - What is the set of independent principles that fully characterize the system?
    - How do we know the complete set of system principles?
      - Vary from 7 to over 100 reported in different articles in literature
- **How do we answer these questions?**
  - Currently looking at Category Theory
    - Provides a mathematical structure for both the function (i.e., objects) and interactions (i.e., relationships or arrows) of the system and the organization
    - Supports integration of system principles into a complete set
      - Need to establish completeness proof
    - Supports definition of system requirements
      - Provides structure to identify complete set
      - Provides structure to establish balance at various levels
    - Supports identification of necessary flow of system information within the organization

System Engineering Operates on the System Principles

- **System Engineering Postulates, Principles, and Hypotheses define System Lifecycle approaches**
  - System Integration
    - System Integrating Physics
      - System Design
      - System Analysis
    - System State Variables
      - Goal Function Tree
      - State Analysis Model
    - System Autonomy
    - Multidisciplinary Design Optimization (MDO)
    - System Value Modeling
    - System Statistics
  - Discipline Integration
    - System Information Flow through the Organization
      - System Dynamics
      - Sociological effects
    - System Thinking
    - Policy and Law considerations

Summary

- **Systems Engineering Framework and Principles**
  - System Integration
  - Engineering Discipline Integration
- **System Engineering Principles encompass System Principles and Organizational/Sociological Principles**
- **Mathematical tools available that offer potential to define system principles and organizational principles structure**
- **System Engineering Principles guide the application of System Engineering Processes**
- **Systems Engineering Approach defined in two documents**
  - “Engineering Elegant Systems: Theory of Systems Engineering”
  - “Engineering Elegant Systems: The Practice of Systems Engineering”

  - Send requests for documents to: michael.d.Watson@nasa.gov

Back-up

- **Note: Reference given at bottom of the last chart for each set of principles**

System Governance Principles

- **Complex Systems Governance Model**
  - 1. All systems are subject to the laws of systems. Just as there are laws governing the nature of matter and energy (e.g. physics law of gravity), so too are our systems subject to laws. These system laws are always there, non-negotiable, non-biased, and explain system performance.
  - 2. All systems perform essential governance functions that determine system performance. Nine system governance functions are performed by all systems, regardless of sector, size, or purpose. These functions define 'what' must be achieved for governance of a system. Every system invokes a set of unique implementing mechanisms (means of achieving governance functions) that determine 'how' governance functions are accomplished. Mechanisms can be formal-informal, tacit-explicit, routine-sporadic, or limited comprehensive in nature. CSG produces system performance which is a function of previously discussed communication, control, integration, and coordination.
  - 3. Violations of systems laws in performance of governance functions carry consequences. Irrespective of noble intentions, ignorance, or willful disregard, violation of system laws carries real consequences for system performance. In the best case, violations degrade performance. In the worst case violation can escalate to cause catastrophic consequences or even eventual system collapse
  - 4. System performance can be enhanced through development of governance functions. When system performance fails to meet expectations, deficiencies in governance functions can offer novel insights into the deeper sources of failure. Performance issues can be traced to governance function issues as well as violations of underlying system laws. Thus, system development can proceed in a more informed and purposeful mode.

  - "Complex system – a set of bounded interdependent entities forming a whole in pursuit of a common purpose to produce value beyond that which individual entities are capable.“

  - "Information and Communications – Metasystem Two (M2) – designs, establishes, and maintains the flow of information and consistent interpretation of exchanges(communication channels) necessary to execute metasystem functions."
    - Communication – the flow, transduction, and processing of information within and external to the system, that provides for consistency in decisions, actions, interpretations, and knowledge creation made with respect to the system."
  - "System Operations – Metasystem Three (M3) – focused on the day to day execution of the metasystem to ensure that the overall system maintains established performance levels.“
    - "Execution – performance of the system design within the unique system context, subject to emergent conditions stemming from interactions within the system and between the system and its external environment."
  - Operational Performance – Metasystem Three Star (M3*) – monitors system performance to identify and assess aberrant conditions, exceeded thresholds, or anomalies."
  - "System Development – Metasystem Four (M4) –maintains the models of the current and future system, concentrating on the long range development of the system to ensure future viability."
    - "Design – purposeful and deliberate arrangement of the governance system to achieve desirable system performance and behavior.
  - Learning and Transformation –Metasystem Four Star (M4*) – focused on facilitation of learning based on correction of design errors in the metasystem functions and planning for transformation of the metasystem."
  - Environmental Scanning – Metasystem Four Prime (M4') – designs, deploys, monitors, and communicates sensing of the environment for trends, patterns, or events with implications for both present and future system viability."
  - "Policy and Identity – Metasystem Five (M5) – focused on overall steering and trajectory for the system. Maintains identity and balance between current and future focus."
  - "System Context – Metasystem Five Star (M5*) –focused on the specific context within which the metasystem is embedded. Context is the set of circumstances, factors, conditions, or patterns that enable or constrain execution of the system."
  - "Strategic System Monitoring – Metasystem Five Prime (M5') – focused on oversight of the system performance indicators at a strategic level, identifying performance that exceeds or fails to meet established expectations.“
    - "Control – invoking the minimal constraints necessary to ensure desirable levels of performance and maintenance of system trajectory, in the midst of internally or externally generated perturbations of the system.
    - "Coordination – providing for interactions (relationships)between constituent entities within the system, and between the system and external entities, such that unnecessary instabilities are avoided."
    - "Evolution – the change of the governance system in response to internal and external shifts as well as revised trajectory.
    - "Integration – continuous maintenance of system integrity. This requires a dynamic balance between autonomy of constituent entities and the interdependence of those entities to form a coherent whole. This interdependence produces the system identity (uniqueness) that exists beyond the identities of the individual constituents."

Keating, C. B., Katina, P. F., Jaradat, R., Bradley, J. M. and Gheorghe, A. V. (2017), Acquisition System Development: A Complex System Governance Perspective. *INCOSE International Symposium*, 27: 811–825. doi:10.1002/j.2334-5837.2017.00395.x

Keating, C. B., Katina, P. F., Gheorghe, A. V. and Jaradat, R. (2017), Complex System Governance: Advancing Prospects for System of Systems Engineering Applications.

System and Organizational Principles

- **Heuristic Systems Principles (Stilleto)**
- **A) H. Sillitto (2014). Architecting Systems: Concepts, Principles and Practice (pp. 33–38)**
  - 1 .A system exists within a wider context or environment.
  - 2. A system is made of parts that interact with each other and with the environment.
  - 3. A system has structure, function, performance, behavior and a life-cycle.
  - 4. A system has system level properties (“emergent properties”) that are properties of the whole system not attributable to the individual parts.
  - 5. A system both changes its environment and adapts to its environment when it is deployed.
  - 6. Systems contain multiple feedback loops with variable time constants.B4. Systems are dynamic on multiple time scales."
  - 7. A system may be part of several wider “containing systems”.
  - 8. A system may have one of three basic types of relationship with its environment: distinct, close-coupled, or fluid and dynamic.
  - 9. A system may offer “affordances” for interaction.
  - 10. Types of systems include technical, biological, social, ecological, environmental and any combination of these.

- **B) G. Mobus & M. Kalton, (2015), Principles of Systems Science (pp. 17–30)**
  - 1. Systemness: Systems are bounded networks of relations among parts constituting a holistic unit. Systems interact with other systems, forming yet larger systems. The universe is composed of systems of systems.
  - 2. Systems are processes organized in structural and functional hierarchies.B9. Systems contain models of other systems."
  - 3. Systems are themselves, and can be represented abstractly as, networks of relations between components.B10. Sufficiently complex, adaptive systems can contain models of themselves."
  - 4. Systems are dynamic on multiple time scales.
  - 5. Systems exhibit various kinds and levels of complexity.
  - 6. Systems evolve.
  - 7. Systems encode knowledge and receive and send information.
  - 8. Systems have regulation subsystems to achieve stability.
  - 9. Systems contain models of other systems.
  - 10. Sufficiently complex, adaptive systems can contain models of themselves.
  - 11. Systems can be understood (a corollary of 9)—science
  - 12. Systems can be improved (a corollary of 6)—engineering

- **C) D. Hitchins (1992), Putting Systems to Work (pp. 60–71)**
  - 1. Principle of Reactions: If a set of interacting systems is at equilibrium and, either a new\ system is introduced to the set, or one of the systems or interconnections undergoes change then, in so far as they are able, the other systems will rearrange themselves so as to oppose the change."
  - 2. Principle of Cohesion: A system's form is maintained by a balance, static or dynamic, between cohesive and dispersive influences. The form of an interacting set of systems is similarly maintained.
  - 3. Principle of Adaptation: For continued system cohesion, the mean rate of system adaptation must equal or exceed the mean rate of change of environment
  - 4. Principle of Connected Variety: Interacting systems stability increases with variety, and with the degree of connectivity of that variety within the environment.
  - 5. Principle of Limited Variety: Variety in interacting systems is limited by the available space and the minimum degree of differentiation
  - 6. Principle of Preferred Patterns: The probability that interacting systems will adopt locallystable configurations increases both with the variety of systems and with their connectivity."
  - 7. Principle of Cyclic progression: Interconnected systems driven by an external energy source will tend to a cyclic progression in which system variety is generated, dominance emerges to suppress the variety, the dominant mode decays or collapses, and survivors emerge to regenerate variety."

- **D) P. Senge (1990), The Fifth Discipline (pp. 57–67); reprinted in B. Lawson (2010), A Journey Through the Systems Landscape (p. 70).**
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System of System Principles 1

- **"A Principles Framework to inform Defence SoSE Methodologies"**
  - Tier 1: World View
    - SoSE ≠ SE"
    - SoSE is multidisciplinary, practice-based and evidence-driven.
    - SoSE is a socio-technical activity
    - SoSE is value-driven
  - Tier 2: Concepts
    - **Methodology Concept:** SoSE methodologies must be tailored to the specific SoS, environments and missions. Blended approaches utilizing multiple methodologies and perspectives that can adapt over time as the SoS adapts are recommended. The complexity of the environment within which SoSE exists requires the understanding of multiple perspectives and multidisciplinary tools & techniques. Methodologies must be tailored to the circumstance, and monitored and adapted to the continual change that is expected in a SoS.
    - **Socio-technical Concept:** SoSE is socio-technical and human-based activity, actively combining organizational, personnel, infrastructure and technical aspects. SoSE requires the alignment of people, organizations, facilities and technology to meet enterprise goals. Trade and resource decisions must balance both technical and non-technical aspects, recognizing that key capability components must often be delivered by non-technical means.
    - **Evolutionary Concept:** SoSE requires an incremental, evolutionary approach; one with long-term goal(s) and phased, implementable milestones that mark clear capability augmentation. The source articles stress the importance of the use of spiral-model deliveries within a broader long-term roadmap, and the need to continuously determine and re-assess milestones based on pragmatic progress and changes in the context.
    - **Stakeholder Concept:** SoSE must make winners of key stakeholders from across the SoS and work within their values. The sources place importance on the essential nature of stakeholder engagement, collaboration and their importance in the identification, development and delivery of SoS engineering and its outcomes.
    - **Resources & Support Concept:** Resources (people, funding and facilities) and governance structures must be agile, collaborative, flexible and innovative [37,45,50,51]. Appropriate resourcing is essential for the success of any activity; however, harnessing resources is a greater issue in SoS where they are usually distributed across constituent system (CS) project offices. Collaboration and innovation in resource utilization is key to ensuring SoS delivery."
    - **Design and Evaluation Concept:** Blended top-down and bottom-up design and evaluation practices are needed to support evolution and increase overall system resilience; these must be light-touch, flexible and adaptive and supported by evidence-based assessments. This concept focuses on technical design as well as evaluation of the constituent systems and the SoS with emphasis on flexible and light-touch approaches to support SoS evolution. The ability of SoSE to both provide and receive direction is seen as essential to adaptivity.

System of System Principles 2

- **"A Principles Framework to inform Defence SoSE Methodologies'**
  - Tier 3: Implementation Principles
    - **Enterprise 1.** Create and maintain a SoSE-aware culture. Stakeholder organisations must intrinsically consider and balance the needs of both the SoS and CS. SoSE guidance should be understood and followed inherently by all those involved.
    - **Enterprise 2.** Training, development and management of SoS Engineers and stakeholders must be structured and specific for SoSE (≠ SE). Key competencies for all stakeholders must be identified and managed. This should be supported by appropriate education and training targeted toward SoSE
    - **Enterprise 3.** The enterprise must take on fundamental responsibilities & provide key services to facilitate SoSE. Enterprises must take on responsibilities such as architecting and developing the SoS, setting and performing governance, sharing information and common tools, and establishing research programs to expand SoSE knowledge and capability
    - **Enterpise 4.** Incentives are necessary to reward and instill good SoSE behaviour. To inspire appropriate behaviour in stakeholders (especially CS staff), the enterprise must incentivise for delivery of SoS outcomes not just CS outcomes. This requires the discovery of the attributes of good SoSE behaviour across the organization

    - **Methodology 1.** SoSE methodologies must be tailored to the specific SoS and seek satisficing not optimising solutions. SoSE does not seek to identify the best or optimal solution; rather itprovides a 'good' or 'satisficing' solution. This places more importance on tailoring"
    - **Methodology 2.** Design strategy and trades are a key focus for SoSE. Throughout SoS evolution, and particularly during initial SoS establishment, understanding & influencing the design methodology and trade spaces at both system and SoS level are key to successful SoSE
    - **Methodology 3.** SoSE is informed (not driven) by a model-based reference architecture, but only as the capability matures. Detailed top-down, architecture-driven approaches are resource intensive, and are not well suited for the initial iterations of the SoS. SoS architecture descriptions have, however, been found to be effective in SoS coordination activities in later iterations
    - **Methodology 4.** SoS owners are responsible for architecting & directing the capability while allowing constituent system owners to manage systems information. Clear roles and responsibilities that support collaboration and efficiency will facilitate SoSE success. System owners provide confidence in systems information while SoS owners deliver clarity in design and evaluation across SoS iterations
    - **Methodology 5.** Use risk management to focus on key SoS aspects/outcomes and ensure balance in effort to achieve satisficing goals. Risk management is used to maintain governance and drive decision making in SoSE, particularly to direct satisficing for the whole SoS rather than optimising for individual systems

    - **Socio-Technical 1.** Balance technical and non-technical aspects in SE trades and resource decisions. Success depends on the ability of SoS managers to work across systems and balance technical and non-technical issues. This requires experienced, capable SoS managers and SE teams
    - **Socio-Technical 2.** Understanding the structures, policy and behaviours of the developer, implementer and user organisations and their interrelationships is crucial to SoSE delivery. Acknowledging and accounting for fundamental SoS stakeholder drivers, including policy, organisational structure and culture, and their interdependencies is essential to ensure the SoS is accepted and milestones are achieved
    - **Socio-Technical 3.** Delivery of organisational, personnel and infrastructure elements is just as important as technical delivery in a SoS capability. SoSE needs to undertake the design tasks holistically and coordinate delivery across all FIC elements
    - **Socio-Technical 4.** SoSE must co-evolve with all FIC elements to realise the potential of the SoS. A typical SoS lifecycle is of sufficient duration for other components, such as strategy, culture, organisations, and doctrine, to evolve significantly. Therefore, SoSE must take their influence into account and reflect their impact
    - **Evolutionary 1.** SoSE should be incremental and evolutionary. Initial SoSE should be investigatory and pragmatic; building and adapting the capability in stages. This principle establishes the need to incorporate new requirements, new technology and other innovations throughout the life of the SoS
    - **Evolutionary 2.** SoSE utilises alternate lifecycle models. Standard lifecycle and development models are not appropriate for SoS capabilities. Fielding staged updates in pragmatic spirals allows the capability to be evaluated and then adapted to the environmental changes expected

    - **Resources 1.** The SoSE team must achieve much of its mission through the CS project offices. The SoSE team is typically small [37] and relies on information and services from other organisational elements, primarily the CS project offices. Project office buy-in and consensus based co-ordination is essential
    - **Resources 2.** Achieve SoSE program robustness through securing resource support across the stakeholder network. Marshalling resources from multiple sources within the stakeholder community encourages commitment, shares the SoS burden and reduces risk while creating resilience for the SoSE program
    - **Resources 3.** Flexible and innovative contracting mechanisms are required to ensure successful SoSE. Contracting arrangements for CS, and SoSE staff must align with the SoSE methodology, context and SoS evolutions. This includes formal and/or informal agreements between CS and SoS engineering teams
    - **Resources 4.** SoSE Facilities, Infrastructure and Tools must be more collaborative, federated and interoperable; and aligned to the methodology. Data consistency and knowledge management are essential. Facilities such as design and decision support environments facilitate communication between stakeholders. System engineering tools to support SoSE arenecessary to support and record design rationale"
    - **Resources 5**. SoS-focussed Modelling & Simulation (M&S) is essential for analysis and assessment. Application of M&S is critical to support planning, trade decisions, and evaluation throughout lifecycle spirals

    - **Stakeholders 1.** Identify & understand each stakeholder's views: who is important & what success means/is for them. This principle directs that it is not enough to simply identify all the stakeholders; it is also important to understand their perspectives, constraints, option/trade spaces, what they value, and what value they deliver to the SoSE outcomes being sought
    - **Stakeholders 2.** Strong and positive stakeholder engagement must be developed and maintained throughout the life of the SoS. Given the independent nature of constituent systems that form the SoS, andtheir asynchronous lifecycles, continuous engagement of all stakeholders is a high priority in SoSE. Close relationships between all stakeholders improves the ability to shape thinking and achieve compromise"
    - **Stakeholders 3.** Treat stakeholders together as groups based on worldviews, roles, responsibilities and interests. Grouping stakeholders assists in stakeholder community development, clarifying needs and focussing decision making (but not for trade-offs – see next)
    - **Stakeholders 4.** Negotiate the standard set of capabilities and plans with key stakeholders. Identify and rapidly deliver their most valued capability. This principle encourages the stakeholders themselves to bargain for their desired outcomes, improves total SoS understanding and maintains commitment by delivering their prized capability"

    - **Design and Evaluation 1.** There is a need for "glueware". SoSE benefits from the use of "glueware" or bottom-up approaches to integration, particularly in early iterations and if the SoS is composed of very independent CS
    - **Design and Evaluation 2.** Open systems concepts and open standards must be used to facilitate the interoperability needed to achieve emergence, adaptability and flexibility. The use of open standards, opensystems techniques, loose coupling, and modularity are crucial to support reconfigurability and interoperability
    - **Design and Evaluation 3.** Adopt a 'design for SoS 'ilities' approach; this will run in parallel with the SoS and constituent system (CS) design activities. SoSE must design for non-functional as well as functional requirements. Non-functional characteristics include robustness, resilience, redundancy and interoperability
    - **Design and Evaluation 4.** Selection of implementation components (at CS level) should be guided by SoS and enterprise needs. CS seek to optimise their own systems often at the penalty of broader integration and SoS/enterprise requirements. Guidance regarding these needs must be provided and rewarded to engage CS
    - **Design and Evaluation 5.** Appropriate and evolutionary SoS Test & Evaluation (T&E) activities, approaches and success criteria must be tailored to the SoS operational need. SoS T&E is fundamentallydifferent from systems T&E. Evaluation and certification activities, processes and acceptance criteria for SoS must be driven by the operational context, objectives, constraints and risks. These must be re-assessed for each spiral. Systems testing must support and build toward integrated capability testing
    - **Design and Evaluation 6.** Utilise test & evaluation (T&E) feedback in development & evolution of the SoS. T&E is intrinsic to SoS lifecycle feedback. It must be used to drive the next phase of SoS evolution.The implications of systems T&E cycles must be used in SoS evolution, T&E and planning in a Kaizen approach
    - **Design and Evaluation 7.** Use Discovery Engineering for continual SoS improvement and to support innovation and derisk capability delivery. Facilities to support experimentation and prototyping are critical to discover SoS capability issues, de-risk integration and extend perspectives. These provide platforms for CS to examine their contribution to SoS emergence and opportunities for innovation and collaboration

Cook S.C., Nowakowski S. and Unewisse M. 2013a. Principles for Designing System of Systems Engineering Approaches for the Australian Defence Force. Proceedings of SETE 2013, Canberra, ISBN 978-0-9752028-7-6.

System Principles 1

- **Systems Theory Propositions**
  - Cicurlar Causality - An effect becomes a causative factor for futrue effects, influencing them in a manner particularly subtle, variable, flexible, and of an endless number of possibilities."
  - Communication - In communication, the amonut of information is defined, in the simplest cases, to be measured by the logarithm of the number of available choices. Because most choices are binary, the unit of inofmration is the bit, or binary digit.
  - Complementary - Two different perspectives or models about a system will reveal the truths regarding the system that are neigher entirely independent nor entirely compatible.
  - Control - The process by means of which a whole entity retains its identity and/or performance under changing circumstances.
  - Darkness - Each element in the system is isgnorant of the behavior of the system as a whole, it responds only to information that is available to it locally. This point is vitally important. If each element "knew" what was happening to the system as a whole, all of the complexity would have to be present in that element.
  - Dynamic Equilibrium - For a system to be in a state of equilibrium, all subsystems must be in equilibrium. All subsystems being in a state of equilibrium, the system must be in equilibirum.
  - Emergence - Whole entities exhibit properties which are meaningful only when attributed to the whole, not its parts - e.g., the smell of ammonia. Every model of systems exhibits properties as a whole entity which derive from its component activities and their structure, but cannot be reduced to them.
  - Equifinality - If a steady state is reached in an open system, it is independent of the initial condictions, and determined only by the system parameters, i.e., rates of reaction and transport.
  - Feedback - All purposeful behaviour may be considered to require negative geed-back. If a goal is to be attained, some signals from the goal are necessary at some time to direct the behavior.
  - Hierarchy - Entities meaningfully treated as wholes are built up of smaller entities which are themselves wholes…and so on. In a hierarchy, emergent properites denote the levels.
  - Holism - The whole is not something additional to the parts; it is the parts in a definite structural arrangement and with mutual activities that constitute the whole. The structure and the activities differ in character according to the stage of development of the whole; but the whole is just this specific structure of parts with their apprpriate activities and functions. (Note: This is a definition of Category Theory)
  - Homeorhesis - The concept encompassing dynamical systmes which return to a trajectory, as oppossed to systems which retrn to a particular state, which is terms homeostasis.
  - Homeostasis - The property of an open system to regulare its internal environment so as to maintain a stable condition, by means of multiple dynamic equilibrium adjustments controlled by interrelated regulation mechanisms.
  - Information Redudancy - The numbe of bits used to transmit a message minus the number of bits of actual information in the message.
  - Minimum Critical Specification - This principle has two aspects, negative and positive. The negative simply states that no more should be specified than is absolutely essential; the positive requires that we identify what is essential.
  - Multifinality - Radically different end states are possible from the same initial conditions.
  - Pareto - 80% of the objectives or outcomes are achieved with 20% of the means.
  - Purposive Behavior - Purposeful vehavior is meant to denote that the act or vehavior may be interpreted as directed to the attainment of a goal - i.e., to a final condition in which the behaving object reaches a definite correlation in time or in space with respect to another object or event.
  - Recursion - The fundamental laws governing the processes at one level are also present at the next higher level.
  - Redundancy of Potential Command - Effective action is acehived by an adequate concatenation of information. In other words, power resides where information resides.
  - Redundancy - Means of increasing both the safety and reliability of systems be providing superfluous or excess resources.
  - Relaxation Time - Stability near an equilibrium state, where resistance to disturbance and speed of return to the equilibirum are used ot measure the property. The system's equilibrium state is shorter than the mean teime between distrubances.
  - Requisite Hierarchy - The weaker in average are the regulatory abilities and the larger the uncertainties of available regulators, the more hierarchy is needed in the organization or regulation and control to attain the same results, if possible at all.
  - Requiste Parsimony - Human short-term memory is incapable of recalling more than 7 plus or minus 2 items.
  - Requisite Saliency - The factors that will be considered in a system design are seldom of equal importance. Instead, there is an underlying logic awaiting discovery in each system design that will reveal the saliency of these factors.
  - Requisite Variety - Control can be obtained only if the variety of the controller is at lease as great as the variety of the situation to be controlled.
  - Satisficing - The decision making process whereby one chooses an option that is, while perhaps not the best, good enough.
  - Self-Organization - The spontaneous emergence of order out of the local interactions between initially independent components.
  - Suboptimization - If each subsystem, regarded separately, is made to operate with maximum efficiency, the system as a whole will not operate with utmost efficiency.
  - Viability - A function of balance must be maintained along 2 dimentions: (1) autonomy of subsystem versus integration and (2) stability versus adaptation.

System Axioms and Principles 2

7 Axioms of Systems Theory

- The **Centrality Axiom** states that central to all systems are two pairs of propositions: emergence and hierarchy, and communication and control. The centrality axiom's propositions describe the system by focusing on (1) a system's hierarchy and its demarcation of levels based on emergence and (2) systems control which requires feedback of operational properties through communication of information.
- The **Contextual Axiom** states that system meaning is informed by the circumstances and factors that surround the system. The contextual axiom's propositions are those which bound the system by providing guidance that enables an investigator to understand the set of external circumstances or factors that enable or constrain a particular system.
- The **Design Axiom** states that system design is a purposeful imbalance of resources and relationships. Resources and relationships are never in balance because there are never sufficient resources to satisfy all of the relationships in a systems design. The design axiom provides guidance on how a system is planned, instantiated, and evolved in a purposive manner.
- The **Goal Axiom** states that systems achieve specific goals through purposeful behavior using pathways and means. The goal axiom's propositions address the pathways and means for implementing systems that are capable of achieving a specific purpose.
- The **Information Axiom** states that systems create, possess, transfer, and modify information. The information axiom provides understanding of how information affects systems.
- The **Operational Axiom** states that systems must be addressed in situ, where the system is exhibiting purposeful behavior. The operational axiom's propositions provide guidance to those that must address the system in situ, where the system is functioning to produce behavior and performance.
- "The **Viability Axiom** states that key parameters in a system must be controlled to ensure continued existence. The viability axiom addresses how to design a system so that changes in the operational environment may be detected and affected to ensure continued existence."

Adams, K. M., Hester, P. T., Bradley, J. M., Meyers, T. J., & Keating, C. B. (2014). Systems Theory as the Foundation for Understanding Systems. *Systems Engineering*, 17(1), 112–123.

System Principles

"Modified Systems Theory Propositions"

- **Boundary** - The abstract, semi-permeable perimeter of the system defines the components that make up the system, segregating them from environmental factors and may prevent or permit entry of matter, energy and information.
- **Incompressiblity** (i.e., **Darkness**) - Each element in the system is ignorant of the behavior of the system as a whole and only responds to information that is available to it locally. As such, the best representation of a complex system is the system itself and that any representation other than the system itself will necessarily misrepresent certain aspects of the original system.
- **Communication** - Communication is a transaction between the information source terminal and the destination terminal, with the sole aim of generation and reproduction of symbols. Information is transmitted as a selection along possible alternative states.
- **Viability** was removed as a proposition (left as an Axiom)
- **Dynamic Equilibrium** - An entity exists as expressions of a pattern of processes of an ordered system of forces, undergoing fluxes and continuing flows of matter, energy and information in an equilibrium that is not static.
- **Power Law** (i.e., **Pareto**)- The probability of measuring a particular value of some quantity varies inversely as a power of that number.

Whitney, K., Bradley, J. M., Baugh, D. E., & Chesterman Jr., C. W. (2015). Systems theory as a foundation for governance of complex systems. International Journal of System of Systems Engineering, 6(1–2), 15–32.

System Pathologies 1

- **System Pathologies Laws, Principles, and Theorems of Complex Systems**
  - **Problem Formulation Utility 1:** This implies, for a practitioner, that there is a need to go beyond the superficial issues and examine the core system issues encompassing structure (e.g., hierarchies) and culture (e.g., policy) of an organization, internal elements (e.g., individual worldviews; resources), and organizational operating environment (e.g., other systems).
  - **Problem Formulation Utility 2:** Systemic intervention cannot be expected without systemic thinking which requires understanding 'systems.'
  - **Problem Formulation Utility 3:** These are not meant to replace other problem formulation methods, but rather act as a complementary perspective for more robust problem formulation for complex systems. In all likelihood, the level of utility of these approaches will vary based on the problem domain, system of interest, and the context of application.
  - **Problem Formulation Utility 4:** Developed pathologies, especially their assessment in an organization, form the basis for design and development of problem formulation and ultimately improvement in a complex system.

  - "**Principle of balance of tensions** - To relieve tensions in complex systems, a metasystem structure must be used to create the right balance between: (1) the autonomy of subsystems and the integration of the system as a whole, (2) purposeful design and self-organization, and (3) focus on maintaining stability and pursuing change. Moreover, there is no 'right' or 'wrong' balance of tensions, rather a 'shifting' balance based on the needs on the system"
  - **Theory of sociotechnical systems** - At the core of this theory is the notion that the design and performance of complex systems can be improved, and indeed can only work satisfactorily, if the 'social' and the 'technical' are brought together and treated as interdependent aspects of a work system. This 'joint optimization' of the technical and social subsystems, that constitute a total work system with neither subsystem being superior to another, is necessary for successful design and operation of a complex sociotechnical system

Systems Pathologies 2

- **System Pathologies Laws, Principles, and Theorems of Complex Systems**
  - Principle of buffering - Stability of systems is enhanced by maintaining a surplus. However, an unused reserve cannot help the system. Whether we are talking about petroleum or wheat reserves or excess capacity to store food or water in the body, the surplus serves to buffer the system against an unexpected increase in demand
  - Principle of circular causality - Any effect becomes a causative factor for future effects, influencing them in a manner particularly subtle, variable, flexible, and of an endless number of possibilities
  - Theory of communication - This theory deals with information especially the process in which a message is coded, transmitted, and decoded. More precisely, transference of meaning between systems by conveying of information, which is done in the bits of information (binary digit). This process aids in control of systems and it is necessary for survivability in changing environments
  - Law of complementarity - Any two different perspectives or models about a system will reveal truths about that systems are neither entirely independent nor entirely compatible
  - Theory of control - The process and means by which a whole system retains its identity and/or performance under changing circumstances. This is might involve moving the system toward a predefined goal involving continuous comparison of current states to future goals through information processing, programing, decision, and communication
  - Principle of darkness - Each element in the system is ignorant of the behavior of the system as a whole, it responds only to information that is available to it locally. This point is vitally important. If each element 'knew' what was happening to the system as a whole, all of the complexity would have to be present in that element"
  - Theory of dynamic equilibrium - For a system to be in a state of equilibrium, all subsystems must be in a floating (not steady orstable) state characterized by invisible movements and preparedness for maintain equilibrium in the midst of change. Moreover,this suggests that systems will stay in their initial condition until some form of interaction is made with them"
  - Principle of emergence - Whole entities exhibit properties which aremeaningful only when attributed to the whole, not its parts—e.g. the smell of ammonia cannot be deduced from the individual elements, only coming about from their interaction. Every model of a system exhibits properties as a whole entity which derive from the interaction of components, but cannot be reduced to individual components"
  - Principle of eudemony - Well-being in complex systems involves morethan financial profitability. It involves a sense of well-being and happiness which might involve the right balance in terms of material,technical, physical, social, nutritional, cognitive, spiritual, and environmental aspects
  - Principle of events of low probability - No system can be all things to subsystems and entities—including people, all of the time.More specifically, the critical fundamental missions of a system should not be jeopardized to accommodate or maximize events of low probability in individual subsystems or entities"
  - Principle of equifinality - If a steady state is reached in an open system,it is independent of the initial conditions, and determined only by the system parameters (i.e. rates of reaction and transport). Hence, taking different paths, the same final state may be reached from different initial conditions"
  - Principle of feedback - All purposeful behavior may be considered torequire negative feed-back. If a goal is to be attained, some signals from the goal are necessary at some time to direct the behavior"
  - Principle of hierarchy - Complex natural phenomena are organized inhierarchies with each level made up of several integral systems. In a hierarchy, levels are said to denote emergent properties of an organization"
  - Principle of holism - A system has holistic properties possessed bynone of its parts. Each of the system parts has properties not possessed by the system as a whole. More specific, it is very important to recognize that the whole is not something additional to the parts: it is the parts in a definite structural arrangement and with mutual activities that constitute the whole"
  - Principle of homeorhesis - This concept encompasses dynamical systems which return to a trajectory, even if disturbed in development. In homeorrhesis, systems return to a particular path of a trajectory while in homeostasis systems return to a particular state
  - Principle of homeostasis - The property of an open system to regulate its internal environment so as to maintain a stable condition, by means of multiple dynamic equilibrium adjustments controlled by interrelated regulation feedback mechanisms
  - Theorem of incompleteness - Typically referred to as Gödel's theorem of incompleteness, this theorem suggests that an effective framework for complex systems cannot be both effective and complete. Thereare always situations that cannot be adequately addressed within the current frame of understanding of complex systems, which must be resolved at a higher level of understanding"
  - Theorem of information redundancy - Errors in information transmission can be protected against (to any level of confidencerequired) by increasing the redundancy in the messages. Redundancy of the messages is required due to 'noise' and thus extra channelcapacity might be required to ensure that the message reaches the intended destination"
  - Principle of least effort - To attain a specific goal, all complex systemswill naturally choose the path of least resistance. For instance, in choosing between adapting to its environment or adapting theenvironment, a system will select the alternative that requires the least expenditure of resources (effort)"

Systems Pathologies 3

- **System Pathologies Laws, Principles, and Theorems of Complex Systems**
  - Principle of minimal critical specification - There are two aspects of this principle, positive and negative. The positive aspect ofthe principle suggests a need for identifying what is essential for design while the negative aspect suggests that no more should bespecified than is absolutely essential for design of complex systems“
  - Theorem of morphogenesis - The ability of complex systems to maintain stability in the context of change conditioned by a morphocatalysis (i.e., conditioned by system contact or co-presence of another system). System-enhancing behavior such as growth, creativity, innovation and change are allowed to remain functional based on other systems. However, it also connotes change in the context of stability inasmuch as stability is required in order for the system to be able to change and to maintain itself in the face of external change
  - Principle of multifinality - This principle suggests that complexorganizations with similar histories and conditions can have outcomes that vary widely. Thus, we can’t draw premature conclusions regarding outcome expectations for different organizations that appear to be operating under similar conditions"
  - Principle of omnivory - This principle suggests that stability in acomplex system is achieved by having a greater number of different resources and of pathways for their flow to the main system components (i.e., modification of internal structures to enable intake of different inputs [resources]. In other words: spread the risks or ‘don’t put all your eggs in one basket’."
  - Principle of Pareto - In any large complex system, it appears thateighty percent of the outputs or objectives will be produced by only twenty percent of the system means. For example, the case whereeighty percent of the shares are held by twenty percent of the shareholders or twenty percent of the sizes (coats, trousers, and shoes) fit eighty percent of the customers"
  - Theory of punctuated equilibrium - The theory suggests that most systems exhibit little net evolutionary change for most of their geological history, remaining in an extended state of stasis (i.e., a period or state of inactivity or equilibrium). However, when such a significant evolutionary change occurs in such systems, it is generally restricted to rare and rapid change that occurs, on a geologic time scale, through a process of cladogenesis (i.e., the process by which a species splits into two distinct species rather than one species gradually transforming into another)
  - Theorem of purposive behaviorism - Complex system purpose must be ascertained through rigorous examination of what the system is producing (e.g., behavior, performance, outputs/outcomes), not what it was intended to produce. Thus, system purpose is directly related to ‘results’ and not attributed to ‘intended’ purpose or desires regardless of the ‘well-intended meaning’ of design
  - Theorem of recursive system - If a viable system contains a viable system, then the organizational structure must be recursive; in a recursive organizational structure, any viable system contains, and iscontained in, a viable system. Thus, the fundamental laws governing the processes, functions, and structure at one level are also present at the next higher level"
  - "Principle of redundancy of potential command - Effective action is achieved by an adequate concatenation of information. In amanagement structure, the potential to act effectively belongs to that subset of management that first acquires the proper information. In other words, power resides where information resides"
  - Principle of redundancy of resources - Generally, maintenance of smooth internal operations and continuous progress towardoverall complex system goals requires redundancy of critical resources. Such resources include, but are not limited to, human, information, or material resources that can be accessed as backup or fail-safe to support achievement of system goals when necessary. Redundancies act to increase the reliability of a system"
  - Principle of relaxation time - It is a characteristic of our society that itsinstitutions (systems)…have a longer relaxation time [recovery time] on average than the mean time interval between massive external perturbations
  - Law of requisite saliency - The factors that will be considered in a system design are seldom of equal importance. Instead, there is an underlying logic awaiting discovery in each system design that will reveal the saliency of these factors
  - Principle of resilience - Complex systems exhibit the ability towithstand, recover from, and reorganize in response to disturbances. This might be characterized by defensive characteristics suchas deterrence, system defensive properties such as physical barriers, capacity, time to repair, availability of warning systems, or critical time"
  - Law of requisite hierarchy - The weaker in average are the regulatoryabilities and the larger the uncertainties of available regulators, the more hierarchy is needed in the organization of regulation andcontrol to attain the same result, if possible at all"
  - Principle of least effort - To attain a specific goal, all complex systemswill naturally choose the path of least resistance. For instance, in choosing between adapting to its environment or adapting theenvironment, a system will select the alternative that requires the least expenditure of resources (effort)

Systems Pathologies 4

- **System Pathologies Laws, Principles, and Theorems of Complex Systems**
  - Law of requisite parsimony - Human short-term brain activity (memory) is incapable of dealing or recalling more than seven plus or minus two items
  - Law of requisite variety - The control achieved by a given regulatorysub-system over a given system is limited by: (1) the variety of the regulator and (2) the channel capacity between the regulator and thesystem
  - Theory of system boundary - Every system has a set of boundaries thatindicates some degree of differentiation between what is included and excluded in the system. Boundary is critical since, too narrow or too broad a boundary gives a false impression of the system of interest—resulting in pursuit of solutions to the wrong ‘system’problem. Boundary identification is necessary to have a minimum description required to distinguish a system from its environment"
  - Theory of system environment - This theory is the basis for suggesting that every system operates in an environment which is always outside the control of the system and yet it (the environment) can influence system processes and behavior. Moreover, since systems do not control the environment, they can only adapt to changes in the environment
  - Principle of buffering - Stability of systems is enhanced by maintaining a surplus. However, an unused reserve cannot help the system. Whether we are talking about petroleum or wheat reserves or excess capacity to store food or water in the body, the surplus serves to buffer the system against an unexpected increase in demand
  - Principle of self-organization - Complex systems organize themselves lacking outside intervention; they exhibit emergentglobal structure and behavior out of interactions of local and seeminglyindependent components [systems, elements or parts]
  - Theory of sociotechnical systems - At the core of this theory is the notion that the design and performance of complex systems can be improved, and indeed can only work satisfactorily, if the ‘social’ and the ‘technical’ are brought together and treated as interdependent aspects of a work system. This ‘joint optimization’ of the technical and social subsystems, that constitute a total work system with neither subsystem being superior to another, is necessary for successful design and operation of a complex sociotechnical system
  - Principle of sub-optimization - If each subsystem, regarded separately, is made to operate with maximum efficiency, the system as a whole will not operate with utmost efficiency. More critically, independent improvement of a particular subsystem may actually worsen the overall performance of the whole
  - Principle of transcendence - Complex systems seem to organize and radiate information in other dimensions beyond physical space-time and mental boundaries of learning, development, and evolution. In such instances material structures are no longer considered the primary reality. God is seen as the source of all being and particularly as the source of evolutionary force, exemplified by that which ‘transcends’ our capability to fully comprehend, existing beyond scientific explanation
  - Principle of satisfying - This is the decision-making process wherebyone chooses an option that is, while perhaps not the best, good enough. In essence, satisfying is attaining a certain minimumquality level for the decision, enough to solve the problem but not necessarily more"
  - Principle of basins of stability - Complex systems have basins of stability which are separated by the thresholds of instability or phases of transition. When acted upon, systems will tend to move into another state (basin) of stability. Thus, a system ‘parked’ on a ridge will ‘roll downhill’
  - Principle of viability - To maintain viability, there must be effectiveorganizational balance maintained along two dimensions: (1) Autonomy of organizational units verses integration of the system as awhole and (2) Stability of operations versus adaptation to changing conditions"

Katina, P. F. (2016). Systems Theory as a Foundation for Discovery of Pathologies for Complex System Problem Formulation. In Applications of Systems Thinking and Soft Operations Research in Managing Complexity (pp. 227–267). Cham: Springer.