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Verification of Requirements: System of Systems Theory, Framework, Formalisms, Validity

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Verification is Third-Party Neutral Process Confirming

- Planning
- Budgeting
- Acquiring
- Developing
- Operating
- Disposing

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of products and services are performed as a lifecycle activity referencing validated requirements.

Verification Roles Focus on Which Requirements

- Roles of verification during system's development
  - substantiate alignment of work to meet requirements (precision)
  - check range of discretionary judgment used to carrying out work (accuracy)
  - formalize acceptance of properties, traits, and attributes of selected artifacts- corporeal intellectual work products

- Verification is essential to assure artifacts produced under the baselined requirements can be used appropriately by others
- THE QUESTION IS: **WHICH REQUIREMENTS**? Systems, system of systems (SoS) or both?

Verification Based on Integration Theory

- Research examines verification within contemporary systems/SoS theory, particularly systems integration.
- Meta-structures encompass lifecycle artifacts of design, architecture, feasibility, capabilities, and operations.
- The objectives:
  - develop methodology to allow requirements of systems to be contextualized within SoS
  - analyze for contributions to SoS
  - evaluate in terms of autonomous operations as well as SoS capabilities

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Integrative approach to contextualizing systems within SoS provides validated set of requirements that can be verified

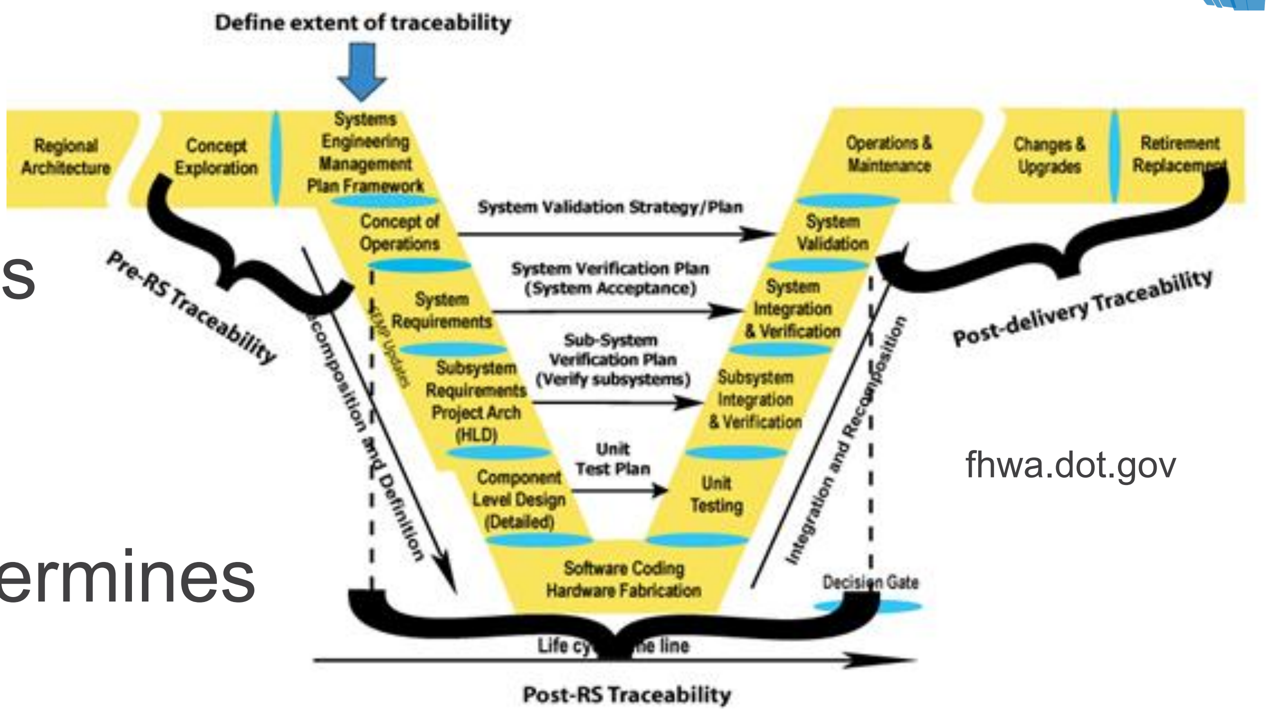
Lifecycle Verification Relies on Traceability

- – process of tracking work products through an unbroken chain of custody and transactions that account for movement, storage, conversion of requirements into goods or services, remnants of work products, association with finished goods or deliverables, and return of work products.
- Traceability of work products is a property of a measurement associated with control of processes.
- Traceability provides for identifying past history, present use, and planned intentions of work products. This identification occurs through the process of mapping the work products through meta-structures to establish and then satisfy the requirements.

Traceability Assumes Full Transparency

- Traceability (assuming full transparency) can be
  - used to monitor work products and test results
  - related to compliance against a performance standard or to verify that a requirement has been satisfied
  - utilized to analyze and evaluate information from a documented, unbroken chain of events – each of which contribute to measurement uncertainty and validating the effectiveness of work products
- Function of traceability is to determine measures and levels of performance(s) that should apply to the need for traceability

Traceability Provides Mechanisms-1



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- Comply with proper procedures
- Reduce misuses of labor for unnecessary work products
- Support an analysis which determines the impact of work products
- Facilitate coordination with stakeholders concerning work products
- Verify work products and use of work products to fulfill requirements
- Provide a method of process control for work products
- Trigger alerts for non-compliance of work products

Traceability Provides Mechanisms-2

- Provide a check to reduce recording errors
- Increase visibility into use of work products
- Promote organizational integrity and focus
- Improve overall effectiveness of requirements validation by formalizing process, including inspection, reviews, reports, to
  - satisfy requirements with work products
  - identify constraints from approved baseline
  - accept units, components, assemblies
  - status integration of units, components, assemblies, and subsystems
  - track and revise forecast for scope

Verification Quality

- Quality of verification determined by validity structures, including:
  - calibration to a standard
  - repeatability of the traceability process
  - implementation error of traceability process
  - mapping of meaningful manifestations from measurement data into information about the use of work products
  - transparency to the extent that all causal items and issues are visible through measurement

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Verification is a Property of Measurement

- “ is an empirical process, using an instrument, affecting a rigorous and objective mapping of an observable into a category in a model of the observable that meaningfully distinguishes the manifestation from other possible and distinguishable manifestations.” (Ferris 2004)
- The validity of measurement and measurement quality requires effective traceability in a rigorous and trusted sense.
- Validity bears on a measuring instrument measuring what it is supposed to measure in context of appropriate theory. Operationalizing traceability requires that its processes be efficacious and its validity be accepted by all stakeholders.

Verification Compliance and Non-Compliance

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- The consistency in variation of data relative to a standard over a period of time or across a variety of tasks presents an opportunity to detect patterns of compliance and non-compliance against a standard.
- Through traceability, compliance or non-compliance is measured to improve the effective acceptance or use of work products.
- Recognizing limitations / constraints ensuing from acceptance, “as built” may be deemed as compliance, albeit temporarily.

Errors in Verification – Precision and Accuracy

- refers to the proximity of two or more measurements to each other. Since, every measurement has error, the lack of precision results in error. High precision also results in error. As the precision increases, the sensitivity to fluctuations increases (Schiller 2009).
- refers to the agreement between a measurement, or observed manifestation, and the real manifestation (Sydenham 1976; Hoffmann 1983); and the notion there is a correct value of the manifestation that can be obtained, and further, that the correct value can be measured (Ferris 2004).

Lifecycle Transparency and Verification - Errors

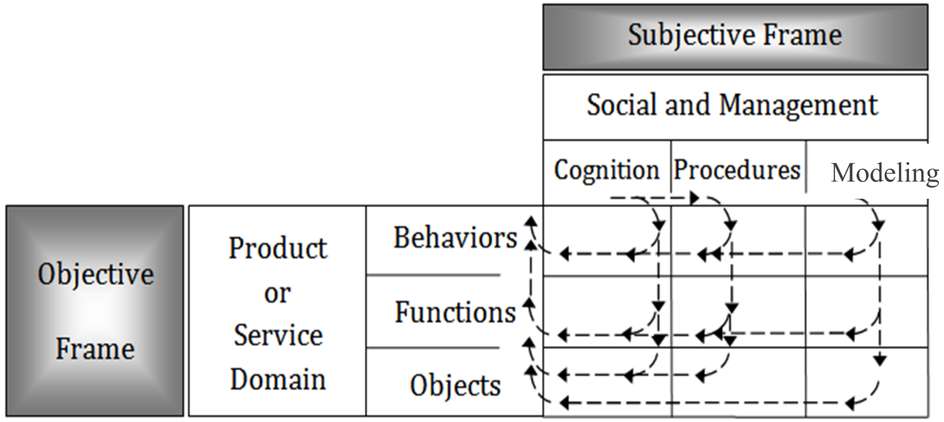
- For lifecycle transparency, the classic definition of accuracy is expanded to a best-case model for providing work products. Measures of accuracy include representing the appropriate information provenance/pedigree, along with information latency.
- Measures of accuracy incorporate errors. These errors lower the accuracy. Lack of accuracy (i.e., inaccuracy) is due to errors that are ordered and planned, but typically invisible. Systematic errors can be estimated. Measures of accuracy are insufficient to account for surprise events and failures of traceability.

Verification and Degree of Transparency

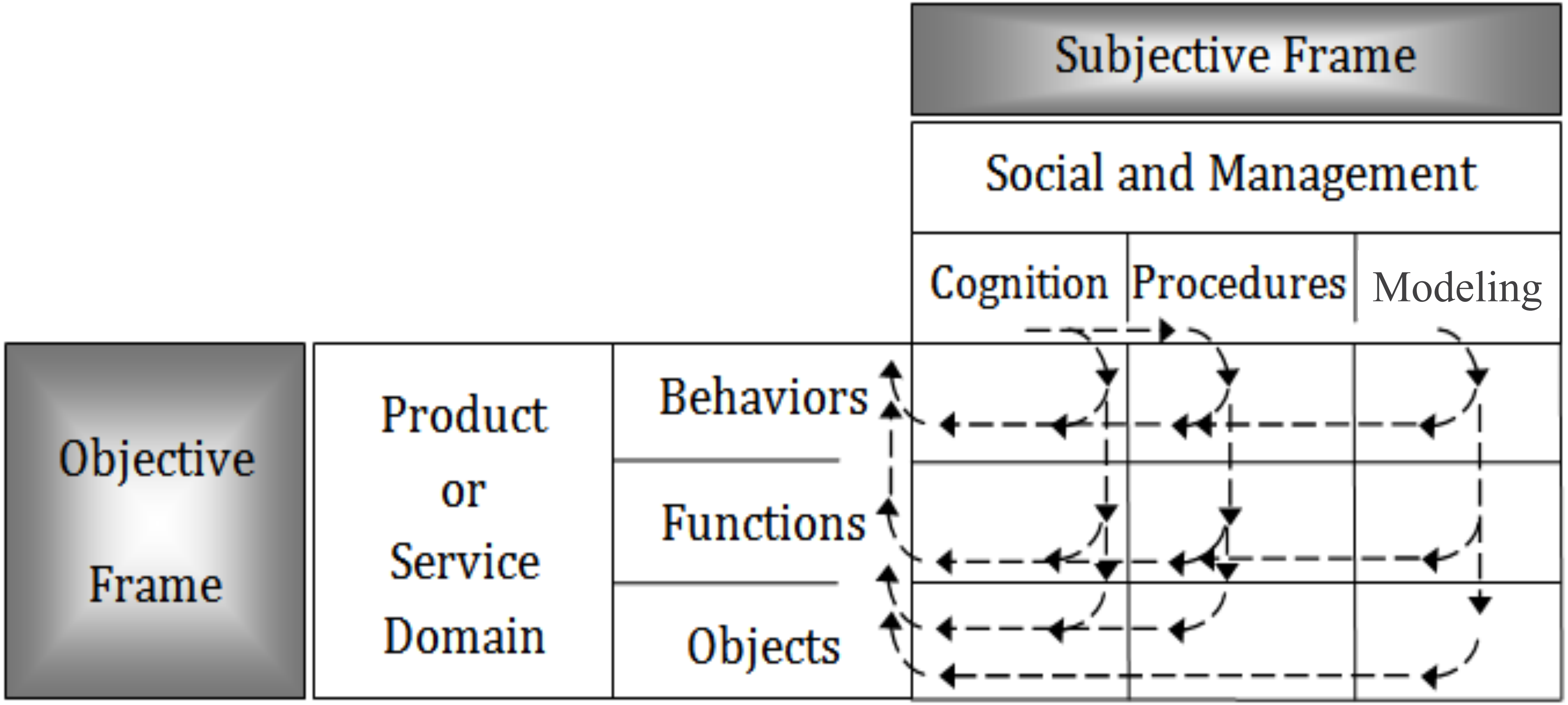
- High transparency, allows work products to be traced backward and forward through their uses, transactions, conversions, returns.
- Complete traceability requires full transparency into all work products.
- A property of measurement permitting encumbered or unencumbered passage of information is termed transparency (NIST 2016).
- Full transparency means full access to complete information and data regarding functionality, performances, and quality. Lack of transparency means access is denied to complete information and data regarding functionality, performances, and quality.
- Transparency describes open access to a particular level of completeness of information and data; and the degree to which functionality, performances, and quality are observable.

Verification in Integrative Framework

- The framework is a model that integrates the frame that describes objects with the frame that describes processes.
  - The object frame is objective, i.e., measurable and quantifiable – independent of our observations; the process frame is subjective, i.e., premised on bias, cognition – dependent on our observations.
  - The objective/subjective framework is described and measured with nominal, ordinal, cardinal, ratio, and interval scaling (Torgerson 1967; Pawson 1989).
  - Verification of work products requires both objects and processes, inclusively.



Integrative Framework Captures Causality



Verification is Process

- The purpose of a general framework of objects and processes is to reveal all possible mechanisms and flows of work products that derive from the activities represented within the framework.
- The framework captures all processes and objects that are specified within the boundaries of the problem domain.
- Attention is paid to requirements, boundaries and boundary conditions, and work products by which interactions occur between objects.
- In most general sense, theory of integration and its integrative framework are valid for all domains, disciplines, and fields of study, i.e., universally applicable.

Verification Research Points out Needs/Req'ts

- Key drivers of causal transactions are needs
- Aggregation of needs to avoid great harm point to requirement(s)
- Needs are not requirements
- Wants are not needs

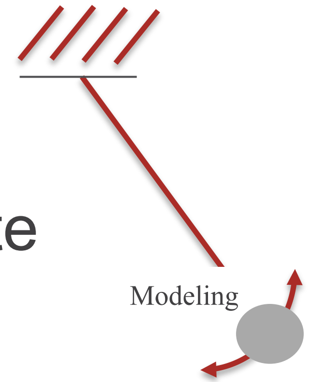
Functions Arise Due to Mechanisms

- "Mechanisms are broadly defined as giving rise to causal regularities" (Dalkin et al., 2015).
- Mechanisms are carried out by individuals who interact with objects and processes (Gabora 1995), and by objects, systems, and processes interacting in various combinations (NASA 2004).
- Mechanisms explain relations between activities carried out by objects. This mechanical explanation relates forces that result in actions.
- Much of the systems engineer's work focuses on mechanisms and interfaces between objects. EMMI that passes between objects at interfaces is enabled by mechanisms. Mechanisms derive from processes.

Process and Function – Physics Based Model

- Processes provide for the capacity to do work. In contrast, a function (different from process) is the means for carrying out work. By analogy, process is akin to force (Feynman 1970) while function is related to energy. ***F = ma***
  - Person raises mass *m* (attached to a string) to a height of 20 cm
  - Person lets mass *m* (string attached to pivot point) swing / oscillate

$$PE = mgh; E = \frac{1}{2} mv^2$$



- Functions are always related to processes, processes provide for the capacity to do work. Energy, Matter, Material Wealth, Information (EMMI) is the capacity to do work.

Verification is Third-Party Neutral Process

- Functions are quantifiable, but cannot be verified.
- Processes can be verified.
- Functions result from interactions between objects
- Uses of functions can be tested.
- Test results can be verified by the process of measurement against requirements for uses of the interacting objects.
- The processes of testing objects and taking measurements can also be verified.

Verification of Emergence

- Emergence is the trait ascribed to a change in constraints, i.e., changes in boundaries or boundary conditions. As with all these definitions and descriptions, the mathematical structures of relationships between objects and processes prescribe strict, consistent definitionals.
- Changes in boundaries and boundary conditions are verifiable. Consequences of changes in boundaries and boundary conditions are measurable (i.e., functions).
- Emergence is a consequence of interaction(s) and therefore, measurable as a functional performance.

Systems of Systems-1

- A is an amalgamation of autonomous systems, the totality of which manifests reciprocal changes in boundary conditions, emergent behaviors, and enhanced functional performances over that of any of its constituent systems.
- SoSs behave like systems with one exception – a system that is part of an SoS must be able to leave the SoS without losing its ability to remain the system that it was before joining the SoS.
- An SoS Shall Do No Harm to the constituent systems.

Systems of Systems-2

- SoS must do no harm to its constituent systems, i.e., no non-reciprocal change. The term, reciprocal, means to have a mutual change. Reciprocal changes in boundary conditions mean that a system that joins the SoS changes its boundaries (and thereby its boundary conditions by which EMMI transacts. These changes extend the boundaries of the SoS.
- On leaving the SoS, the system reverts to its previous boundaries, the influence of the leaving system no longer having an effect. Emergent behaviors in a SoS result from the interactions between the constituent systems. Those emergent behaviors change with joining or leaving the SoS.

Verification for Systems of Systems-1

- Verification within the structures of a SoS must respect the autonomous nature of individual systems as well as the synergy and benefits derived from interacting within a SoS. A SoS can be thought of as a set of meta-structures that encompass the cause, ideology, utility, practice, and methods of all constituent systems.
- A goal of a SoS-to-A meta-structure is to abstract lifecycle artifacts of design, architecture, feasibility, capabilities, and operations.

Three Objectives Must Be Met

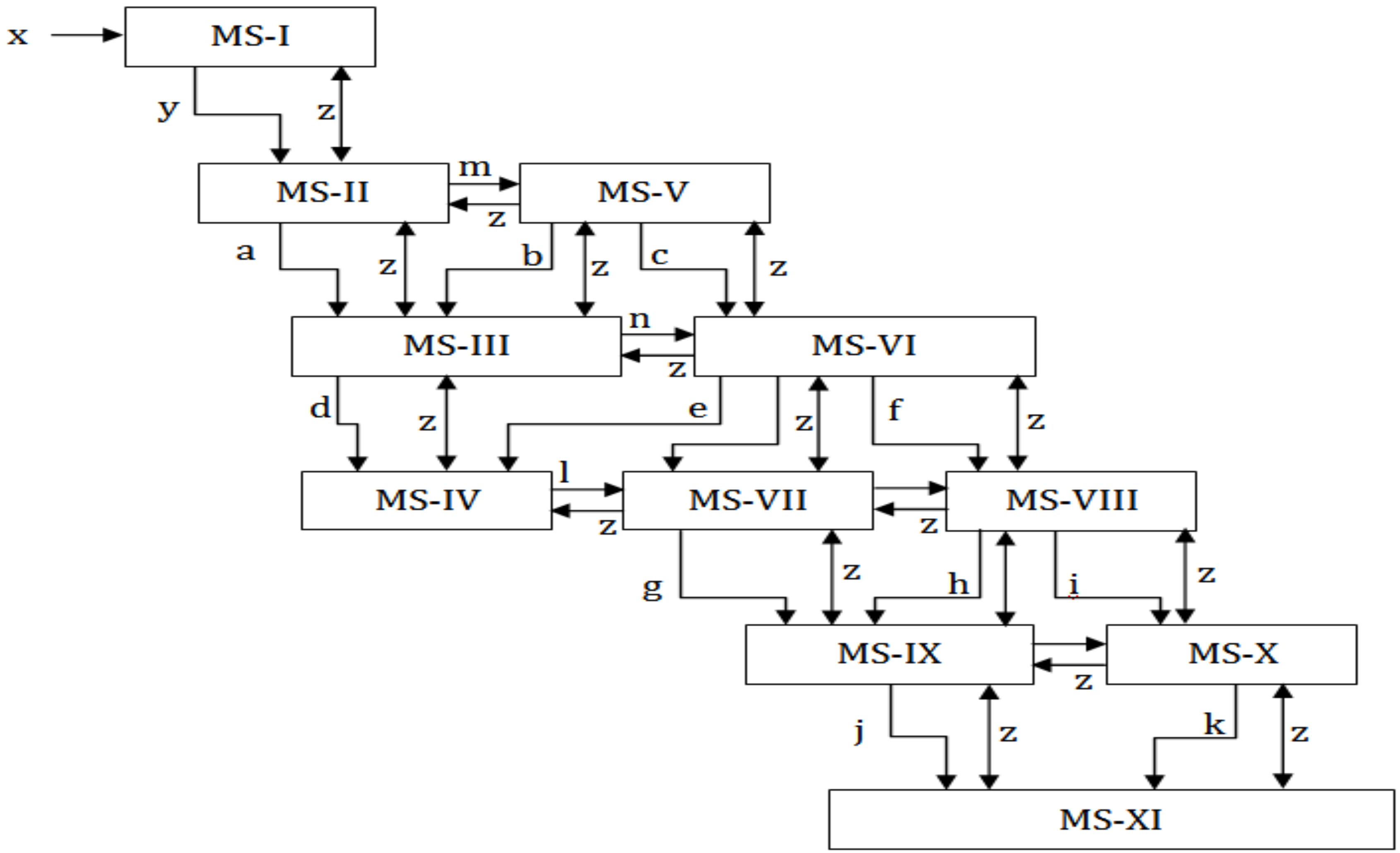
- First, the implementation of a SoS must allow requirements of individual systems to be contextualized within growth and updates envisioned for systems within the SoS.
- Second, the architecture of each system needs to be analyzed to provide for integration and interoperability into the SoS.
- Third, the systems and the SoS need to be evaluated in terms of functional performances and quality.

Such an integrative approach to contextualizing systems within the SoS should provide for a validated set of requirements from which verification can be carried out.

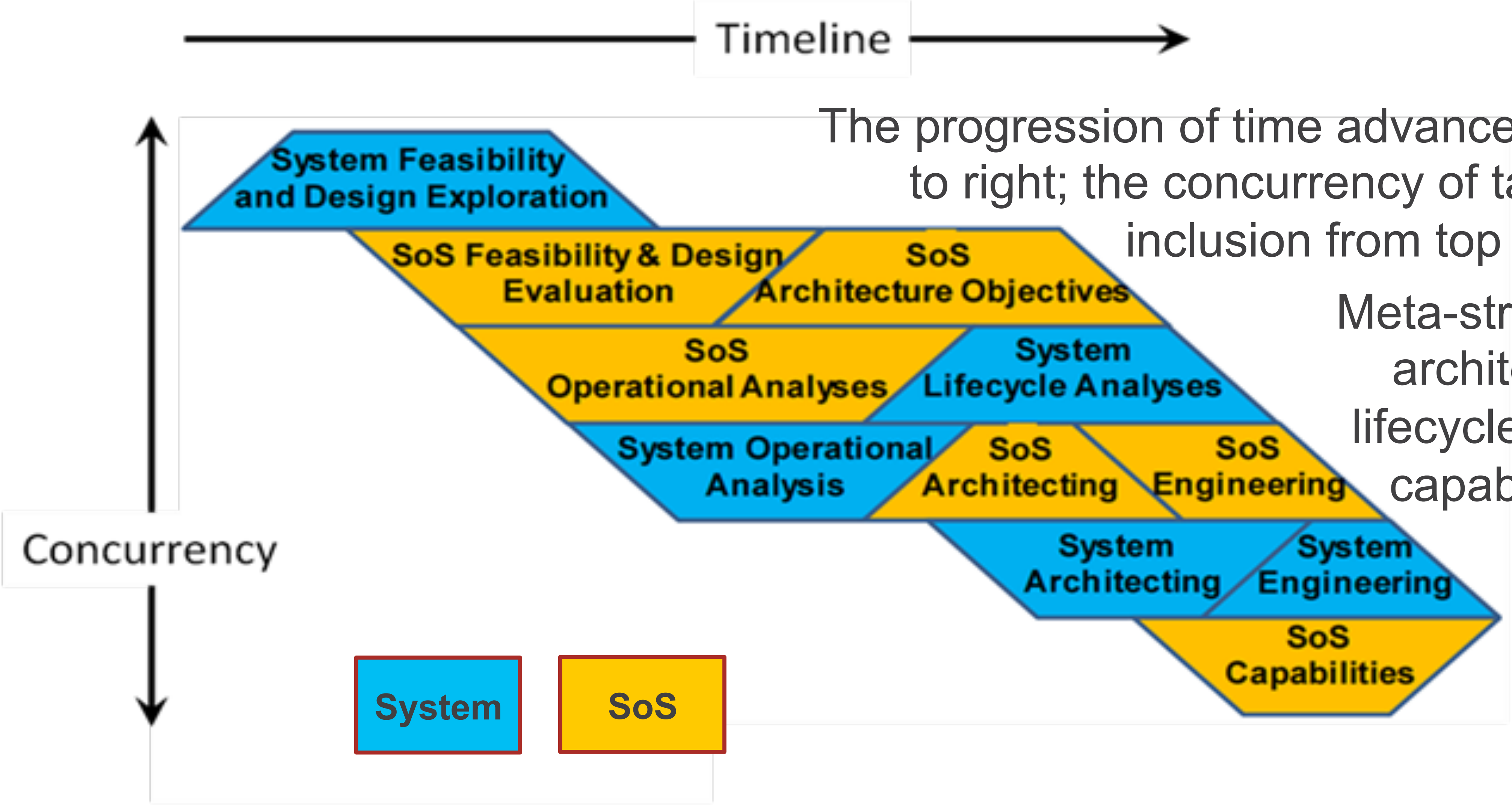
Domains of Congruence

- The domains of congruence are established between systems and the SoS to provide the meta-structures which control the changes for systems and the SoS to be integrated and made interoperable (Pavard et. al, 2006).
- Development of a formal model found eleven meta-structures that controlled the requirements for a SoS and constituent systems. Five of these meta-structures were based on the design-architecture-operations, i.e., objects, and processes that makeup the individual systems. Six of these meta-structures were established from the range of SoS enhancements that were planned to augment the individual systems.

SoS Meta-structure Transaction Structures



SoS Meta-structure Integration Process Model



The progression of time advances from left to right; the concurrency of tasks show inclusion from top to bottom.

Meta-structures for design, architecture, operations, lifecycle, engineering, and capabilities are covered.

Verification of SoS Requirements

- From formal theory of systems integration and a physics-based foundation for functions and processes, this research formulates a standardized systematic approach to verification of requirements for a SoS *and* each of its constituent systems.
- Verification within an object-process framework to both systems and SoS requirements is tractable and established with mathematics. The result is 11 meta-structure activities that provide inputs to a typical systems engineering process model.
- Therefore, domains of congruence are established between systems and the SoS to provide the meta-structures which control the changes for systems and the SoS to be integrated.