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G. Reza Djavanshir, M. Jafar Tarokh
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Meta-Systems

G. Reza Djavanshir
Carey Business School, Johns Hopkins University, Baltimore, Maryland, U.S.A.
M. Jafar Tarokh
K.N. Toosi University of Technology, Tehran, Iran

Abstract
A meta-system, a type of system of system that is capable of dealing with emergent events, is described. The characteristics of such a system, its architecture and governance are also presented.

INTRODUCTION

The study of system-of-systems (SoS) has become a central research discipline. SoS is particularly gaining importance because of its tremendous and vast applications in engineering, infrastructure development, strategic management, and net-centric and extended organizational development, to name a few. However, despite all these applications, SoS is loosely defined and often misunderstood. Furthermore, the design and deployment of various types of systems, particularly extended net-centric organizations and globally networked supply chains, go beyond what is referred to in the literature as SoS; rather, they necessitate an understanding of meta-systems.

A meta-system is a viable SoS. By viable system, we mean a system capable of maintaining resilient existence when it is dealing with unpredictable emergent events or threats from its uncertain environment. Therefore, in order for any SoS to be viable, it must be a meta-system. In this entry, we also emphasize calling the SoS the meta-system, for several reasons:

- The term SoS was originally used by Ackoff in a different context, as he was trying to provide a system or a set of concepts and definitions to better define and describe systems. According to Ackoff, thus far, “The concepts and terms commonly used to talk about systems have not themselves been organized into a system. An attempt to do so is made here.”
- It is the meta-system that has powerful mechanisms and structures that make SoS’ architecture and integration possible and provides the necessary structure to deal with critical issues such as its complexity and unpredictable emergent events.
- According to Keating, “It is the meta-system that structures the appropriate balance to relieve the tensions, (i) autonomy of subsystems and the integration of the SoS as a whole, (ii) purposeful design and self-organization, (iii) focus on maintaining stability or pursuing change.”
- Finally, SoS is indeed a meta-system.

Therefore, in this entry, we emphasize calling the general SoS, and viable SoS in particular, with its real name, that is, the meta-system. We will attempt to provide a definition of meta-systems and their characteristics and properties.

Meta-systems are large-scale systems whose components are geographically distributed networked systems. The main objective of each individual component system is to serve the strategic goal and mission of the meta-system.

Component systems of the meta-system are semi-autonomous heterogeneous enterprise systems composed of sociotechnical, human, organizational, hardware, and software elements. By semi-autonomous, we mean that some degree of managerial flexibility or flexible control is provided to all the geographically distributed component systems for managing their local operations and program management. This includes issues such as maintenance, resource acquisitions, removal, or upgrades of distributed systems. The flexible control also enables the distributed components systems to balance tensions such as maintaining autonomous managerial functions while being an integral part of the entire meta-system.

A critical component of the meta-system is its centralized governance and support system (GASS), which guides, coordinates, and oversees the design, deployment, and operations of enterprise systems. Furthermore, various components of any meta-system often have predefined change, replacements, or transition strategies which require governance and support structures to formulate and implement new changes and prevent the meta-system from falling into unstable conditions.

The GASS also provides strategic architecture that articulates the meta-system’s strategic goals, policies, and
operational standards, as well as the core capabilities needed to achieve them. The capabilities provided by the GASS also include managing crises, dealing with unpredictable complex emergent events, and responding to threats and opportunities in uncertain environments.

The design and operation of GASSs are based on three main networks, namely: 1) the integrated communications and learning network for information sharing, command, and control signals; 2) the infrastructures’ network which includes facilities, hardware and software platforms, and technological artifacts; and 3) the institution’s network which includes organizations, people, centralized management, command, coordination, and control mechanisms. The GASS uses these three networks to provide the following critical functions:

- Formulate overall strategies (strategy architecting) and policies that define the meta-system’s strategic goals and mission.
- Act as focal structures to steer the implementation of the overall strategy and provide regulative and consultative services.
- Ensure compliance with the adapted standards and policies.
- Formulate the required transition strategy for managing changes and controlling the transitions process.
- Balance operational tensions including local–central control and ensuring the meta-system’s stable operations, and prevent the meta-system from falling into chaos.
- Gather and disseminate intelligence and useful information about the uncertain environment and identify possible threats and opportunities.

Therefore, defining and understanding the GASS as an integral part of the meta-system’s design and operation is critical to its viable operations, particularly during unpredictable emergent events and the structural transitions of the meta-system.

This entry will be composed of five sections: Section 1 will provide an introduction, Section 2 will provide the definition of the meta-system and its characteristics, and Section 3 will provide the description of, and the rational for, a centralized GASS in the meta-system. The design and deployment of the meta-system are discussed in Section 4. Finally, Section 5 will provide a conclusion and recommendations for future research.

**WHAT IS A META-SYSTEM?**


The meta-system is a large-scale distributed system, comprised of distributed heterogeneous enterprise systems that are integrated and networked together by its GASS to accomplish a shared strategic goal.

The component meta-systems are enterprise systems composed of technological artifacts and organizational, managerial, human, and informational elements. These heterogeneous elements are integrated together to create capabilities and capacities for achieving a desired shared strategic goal. The meta-system structures and integrates these heterogeneous components through its governance structure, which is based on three networks: physical, social, and information. However, to provide a comprehensive and robust definition of a meta-system in dealing with various complex emergent problems and uncertain environments, we expanded Dagli and Kilicay-Ergin’s definition of three integrated networks (I3N) (the physical, social, and information networks) to include critical elements, such as: communications, information sharing, learning, knowledge accumulation mechanisms, and institutional elements that govern the dynamics of a meta-system’s behaviors. Therefore, based on our studies of various literatures including Beer,[1,3] Ashby,[15] Keating,[5] Kawalek and Wastell,[13] Buede,[9] and Dagli and Kilicay-Ergin,[4] a meta-system should possess a system that governs and provides support services to all enterprise systems within the meta-system and, as we will discuss in this entry, it is the GASS contained in the meta-system that makes the meta-system viable. The GASS in the meta-system is created by the nexus of three networks: 1) an integrated communications and learning network for information and knowledge sharing, learning, command, and control signals; 2) an infrastructure network that includes facilities, hardware and software platforms, and technological artifacts; and 3) an institution’s network such as organizations, people, management rules, command, coordination, and control mechanisms. These I3N are described as follows:

1. **Integrated communications and learning network** contains various multimedia communication networks, the Internet and Intranet, and learning channels providing information flows and knowledge sharing mechanisms that are essential to the meta-system’s viable operations, particularly its effective functioning during uncertain and changing environments. This network carries signals, knowledge, and a constant exchange of information among the meta-system’s components, which enables the meta-system to deal with emergent events, crises, threats, and opportunities. In addition, it facilitates the emergence of self-organizing structures during the system’s perturbations and chaotic situations by
providing error detection, feedback, fault isolation, and correction.[5]

2. **Infrastructure network** includes all technological artifacts, hardware and software tools, platforms, supply chains, transmission grids, and other resources that support the functioning and operations of the meta-system.

3. **Institution’s network** is composed of organizations, people, processes, and governance mechanisms that provide strategies, guidance, rules, policies, standardized interfaces, and operational protocols along with various regulative, normative, and cultural-cognitive elements that are necessary for the coherent integration and operation of the meta-system. A critical element in the institution’s network is the GASS that coordinates and oversees the meta-system’s design, integration, deployment, and operations to achieve its strategic goals.

**Characteristics of the Meta-System**

As we discussed in the previous section, the meta-system is comprised of I3N of various elements such as infrastructure, information, institutions, people, organizations, technological artifacts, and hardware and software platforms. In other words, the components of a meta-system are enterprise systems whose elements come from I3N, and the meta-system provides the synchronized integration of all the distributed enterprise systems, governing their operations by offering guidance, coordination, and overall strategy (strategy architecture). A critical task for the governance mechanism is to ensure the meta-system’s stable operations to accomplish its strategic goal and mission. The governance mechanism also oversees the use of standardized interface protocols throughout the entire meta-system to ensure interoperability among its components. The meta-system also possesses specific characteristics that are described in the following section:

- **Heterogeneous elements**: The meta-system is comprised of various interdependent enterprise systems whose elements can include hardware and software platforms and technological artifacts, institutional elements such as people and processes, and infrastructures, information, and communications networks.

- **Semiautonomous enterprise systems**: The components of the meta-system are semiautonomous enterprise systems with operational and managerial autonomy,[4,16,17] however, they should operate under the governance and support mechanism of the meta-system to achieve their shared strategic goal and to avoid falling into unstable conditions. In the context of the meta-system, semiautonomy also means that enterprise systems are independently operable systems on their own, but they are networked and integrated together to achieve the meta-system’s strategic goal.[4] Therefore, enterprise systems exist for the purpose of serving the meta-system to achieve its mission (Luhmann, 2003 and Kauffmann, 1994). In other words, although the desired outcomes expected from each enterprise system, along with the overall framework of the strategy (strategy architecture), are defined by the meta-systems, flexible-control is also provided to allow each enterprise system to manage its own local operations, detailing, and execution as part of the overall strategy. The semiautonomy of distributed enterprise systems also implies that these systems do not possess full independence from the meta-systems that govern them but rather the systems are integrated to achieve the meta-system’s strategic goal and to prevent its operations from falling into chaos. For example, an enterprise system does not have the authority to make strategic decisions critical to the survival or failure of the meta-system, nor can an enterprise system make decisions that contradict the meta-system’s overall strategy. Therefore, the enterprise systems are autonomous in making tactical decisions and they are autonomous in managing their own programs and running their daily operations in terms of scheduling, maintenance, and resource acquisitions.

- **Topologically distributed enterprise systems**: Enterprise systems are also geographically dispersed at global, national, or local levels. These systems are linked to the GASS through integrated communications, institutions, and infrastructure networks with constant communication and the flow of resources, materials, information, and strategic decisions to achieve the meta-system’s overall strategy and its goal.

- **Commensalism and symbiotic relationships**: Commensalistic and symbiotic relationships exist among enterprise systems and also between the meta-systems and all of their component systems. Commensalism and symbiotic relationships mean that intertwined, interdependent, or partially interdependent entities use each other (commensalistic relationship) and help each other (symbiotic relationship).[18]

- **Evolutionary self-producing process**: Meta-systems are developed through evolutionary and adaptive processes, where the components of the meta-system are modified, removed, added, or reconfigured in response to new requirements and changes, threats, or opportunities in the environment. Furthermore, as the environment evolves, the meta-system’s requirements, boundaries, architecture, and configuration should change and coevolve as well to adapt to it. Therefore, the meta-system’s requirements, configuration, and final design are always incomplete, and its
boundaries are in flux. In addition, as we discussed in previous sections, the enterprise systems are created and integrated together by the meta-system, while the meta-system itself exists by means of its interacting enterprise systems. This process of the cocreation of the meta-system and its component enterprise systems results in the self-production (Autopoiesis) of the entire meta-system. In other words, as the environment evolves, the meta-system redesigns and reproduces itself to adapt and respond to new conditions in a coevolutionary manner. Coevolution means that as intertwined and interdependent entities adapt to their environment over time, they also coadapt to and coevolve with each other. The coevolutionary processes within meta-systems also take place through communications and learning networks, as the enterprise systems interact with each other, exchange information, share knowledge, and coevolve. According to Dagli and Kilicay-Ergin, when a component enterprise system is reconfigured without changing its interactions, links, or interfaces to other systems, the evolutionary transition process takes place. The coevolutionary transition of a meta-system starts in response to the evolution of the environment and to the shortcomings of existing policies, design, and technology options. By reexamining the current technologies, architecture, and design against the changed environment, gaps are identified, as are new requirements and technological options. Therefore, the system is recreated and the system is reproduced, in other words, the meta-system reproduces itself with a new design in response to the continuously evolving environment and new requirements. The spiral process of self-reproduction (Autopoiesis) and transition of a meta-system from one state of design to another requires dynamically coevolving designs and architectures. However, the reproduction of a meta-system’s new design should take place in a way that allows its strategic framework and core architecture to remain invariant (homeostasis); otherwise, the resulting meta-system can be dysfunctional.

- **Emergence property**: There are two related forms of emergence properties in any adaptive system—Type I and Type II. Type I is intentional and by design, where new capabilities, behaviors, and properties emerge from the process of structural interactions among the meta-system’s components. Type II is the unintended consequence of not knowing about the emergence in advance. This unpredictable behavior comes from the interactions of the meta-system within an uncertain and unpredictable environment. With respect to the unpredictable environment and the emergence of unintended consequences, the detailed design and specifications of a meta-system should not be specified in advance of its operation. Rather, the detailed knowledge and information about the meta-system’s design should be part of the design, operations, and implementation process. In other words, the system design should be based on the law of minimum critical specifications. Otherwise, a detailed design and specifications would increase the system’s complexity, which creates a structural sclerosis restricting the meta-system’s agility, adaptability, and responsiveness to the evolving uncertain environment. This kind of sclerosis can result in unintended consequences, and it also restricts the meta-system’s capacity to self-organize and self-produce based on the contextual information.

**GOVERNANCE AND SUPPORT SYSTEM**

Meta-systems possess a GASS that shapes and synchronizes the collective actions and integrations of the enterprise systems in the meta-system by providing strategy, direction, guidance, and coordination, as well as by overseeing the meta-system’s operation in achieving its mission and objectives. In addition, the GASS is also responsible for balancing operational tensions within the meta-system and facilitating the emergence of self-organizing structures during the meta-system’s perturbations.

Furthermore, the governance and support structure is in constant interaction with all distributed enterprise systems through the meta-system’s I3N, which we discussed earlier in the entry, by flow of information sharing, resources and capital, and strategic decisions. However, it does not provide detailed strategic plans, nor does it manage the detailed and daily operations of its distributed enterprise systems. That is, loose-coupling or flexible control is provided to deal with the paradox of centralized power and control by encouraging semi-autonomous local operations of the enterprise systems within the framework of the meta-system’s strategy (Well and Sage, 2009). In addition, meta-systems are complex constructs. Their complexities, coupled with the uncertainty of the environment, overwhelm the capacity of a centralized GASS to fully understand, control, or micromanage its distributed component enterprise systems. Therefore, the GASS should be loosely coupled with all distributed enterprise systems. In other words, the role of a GASS is not to get involved in the detailed management of its enterprise systems’ operations but rather to provide strategic frameworks and guidance necessary to facilitate collaboration among its enterprise systems and to ensure stable operations and the emergence of self-organizing orders during unpredictable systems’ perturbations.

In order to provide an effective response to opportunities, threats, and changes in its evolutionary
environment, the meta-system must have a strategy architecture that manages the changes and transitions. However, the strategy architecture is not a detailed change plan; rather, it articulates the meta-system’s mission and desired goals, providing a general framework and description of how the meta-system can accomplish its desired mission. The strategy architecture should be based on the assumption that the detailed information about a change is part of the change process. That is, it cannot be fully preidentified due to the lack of full information about uncertain future events. Therefore, flexibilities should be allowed in terms of the strategy’s details and its execution and implementation.

Moreover, not every enterprise system has the means to create fair and balanced shared policies that meet the interests of all other enterprise systems. Therefore, a GASS is needed to resolve the operational tensions and suboptimizations at the local level, and to promote cooperative and coevolutionary behaviors among various geographically distributed enterprise systems. This system must also accomplish a common good among enterprise systems. The need for a GASS is also articulated by DeRosa and can be summarized as follows:

1. Formulate, enforce, and manage common standards, particularly interoperability interface standards, throughout the entire meta-system.
2. Develop strategy architecture that defines the desired outcome to be achieved by the meta-system, as well as defines the capabilities expected from the enterprise systems in order to achieve the strategic goal. Component systems should collaborate to collectively provide the expected functional capabilities and capacities in achieving the meta-system’s strategic goal and mission.
3. Facilitate the flow of information, capital, resources, and strategic attributes such as fitness rules and interface standards.
4. Facilitate the creation of a dynamic equilibrium that maintains the stability of the meta-system during internal and external changes and turbulence. Dynamic stability is achieved through adjustments to changes, shifts, and disturbances (Skyttner, 1996). Therefore, during unstable, unpredictable emergent situations, a new order of behavior and structure emerges that allows the meta-system to maintain its stability. The GASS provides the necessary information, guidance, and coordination and it also encourages teamwork and communications that are required for self-organizing patterns to emerge out of chaotic situations.
5. Balance the tensions between local autonomy and centralized control; differentiations (diversity) and integration (stability); laissez-faire self-organization and detailed design and operational strategy; cooperation and competition; and individual enterprise system’s self-interests (optimizing local benefits) and the achievement of the common good among all enterprise systems.
6. Update and redefine the meta-system’s fitness criteria (requirements) to avoid unstable or complex conditions. In high velocity changing environments (“fitness landscape”), design requirements (“fitness rules”) should coevolve with the changing environment (“fitness landscape”).

The meta-system’s design requirements, its interface standards, or the overall fitness rules are shaped by the collective efforts of the meta-system’s GASS in collaboration with enterprise systems. According to DeRosa, the fitness criteria should coevolve with changes in the environment (fitness landscape); therefore, the GASS should constantly re-examine and redefine the fitness criteria. To do so, it should obtain feedback, update information, and make the necessary changes to the fitness criteria. The GASS creates policies and incentive structures, and it leverages a cooperative game approach to align the interests and functional operations of individual enterprise systems with the shared interests of all enterprise systems. This approach will, in turn, aid in the achievement of the meta-system’s strategic goal. In cases where an individual component enterprise system pursues its own self-interests, the GASS should create conditions and incentives that benefit all enterprise systems.
META-SYSTEMS’ DESIGN AND FUNCTIONAL OPERATION

In previous sections we provided the definition and characteristics of the meta-system and we emphasized the importance of its GASS. We also showed that the design, deployment, and operations of the meta-system are based on three networks: 1) integrated communications and learning network; 2) infrastructure network; and 3) institution’s network. These networks are built into the meta-system’s design to provide the following critical functions:

- Monitor, govern, support, and maintain the meta-system’s stable operations.
- Provide mechanisms for information and knowledge sharing, resource allocation, and flows of command and controls.
- Provide optimum alignment, allocation, and deployment of resources according to the dynamics of the meta-system’s internal and external environments.
- Facilitate conflict resolution and balance the operational tensions between maintaining the status quo (homeostatic structure) and change (morphogenesis), detailed design, and self-organization.[5]
- Respond to threats and opportunities in an uncertain environment.
- Facilitate the emergence of self-organizing, stable order during the meta-systems’ unpredictable perturbations.

The above-mentioned critical functions of the GASSs are performed by five interacting subsystems that support, govern, coordinate, guide, and oversee the operational functioning of enterprise systems.[1, 3] These subsystems also identify and respond to opportunities, threats, and emergent events in the uncertain environment. The functionality possessed by each of these subsystems is described below.

An important question in the design and deployment of the meta-system is what form of internal architecture and design is needed to make it viable.[13] Beer’s response to this question is based on the Law of Requisite Variety.[2] This law says that, for a system to be viable, the variety of regulator must be more than or equal to the variety of the regulated systems. By variety we mean the number of possible architectures and designs of a system. In the context of the meta-system design, this explains why meta-systems with detailed designs, or those with a large number of requirements, will have unintended consequences once their designs are deployed due to unpredictable changes in the environment or incomplete information about any future emergent event; in other words, the design of a meta-system can only be partially specified in advance.[5]

Hence, to ensure viability and the effective response of the meta-system to its uncertain and evolving environment, it must be designed with a minimum of critical requirements (regulations). In systems’ design methodology, this concept of minimum critical regulations is known as minimum critical specification.[5, 21, 22] In this sense, maximum flexibility and agility of the meta-system is preserved, and therefore its maximum responsiveness to unpredictable perturbation is ensured.

In addition to the law of minimum requirement specifications, we believe there are two additional complementary issues that make the meta-system viable. These are: 1) standardized interconnectivities and interfaces; and 2) the modular design and deployment of the meta-system with the minimum possible connectivity.

Meta-System’s Deployment and Maintenance

Thus far, we have described the characteristics, design, and functional operation of the meta-system. Now let us describe its deployment and maintenance processes. Let us assume that we are tasked with designing or redesigning one or more of the enterprise systems experiencing problems within a given meta-system. As shown in Fig. 2, the meta-system contains other enterprise systems along with the GASS that together are pursuing the meta-system’s strategic goal and mission. The GASS is also providing guidance, strategy architecture, logistics, and supplies and is overseeing the redesign, upgrade, or replacement of the faulty enterprise system.

To understand how to diagnose fault, resolve the problem, or design and deploy the enterprise system, the GASS needs to understand the entire meta-system, including the structural interactions between the enterprise system to be replaced and other systems in the meta-system, as well as the environment or context of the meta-system.[9, 14] The GASS must also re-examine the assumption, framework, and context of the problem in order to be effective in diagnosing and resolving the problem.

After the problem is resolved, the design and deployment of the new enterprise system may introduce new unintended problems (i.e., emergent behavior) as well. However, as we discussed, such unintended consequences or unpredictable emergent behaviors arise due to one or, or combinations of, the following issues:

- Systemic interactions among the meta-system’s components or the meta-system itself with its unpredictable environment.
- Imperfect information about the environment or the context in which the meta-system is designed, deployed, and functions.
The Meta-System at Time (T)

The Meta-System at Time (T+1)

Fig. 2 Meta-system’s evolutionary design and deployment.
• The bounded rationality of the human elements that designs, operates, governs, and supports the system.\textsuperscript{[123]}

In addition to the introduction of potential emergent behavior, after the new enterprise system is deployed, the GASS should redesign or, it is better to say, reproduce itself (Autopoiesis) in order to adapt to and coevolve with new changes in the environment or the context of the meta-system. Additionally, in order for the upgraded meta-system to adapt to and coevolve with its changing environment, the deployment of the new enterprise system must be aligned “optimally” with the internal and external environment.

CONCLUSION AND RECOMMENDATIONS

In this entry we provided a definition of the meta-system and its main characteristics. A meta-system provides the structure, processes, and GASS that integrate and synchronize operational capabilities to create a viable SoS. The meta-system is comprised of GASS as well as networked enterprise systems consisting of people, technological artifacts, infrastructure, resources, communication and learning networks, organizations, and regulative, normative, and cultural cognitive institutions. Meta-systems coevolve with their changing environments (sometimes with high velocity) and in order to adapt to these changes, the meta-system’s requirements and specifications are incomplete. Therefore, the coevolutionary process of transitioning and self-reproduction (Autopoiesis) of a meta-system from one state of design and operation to another requires dynamically coevolving architectures and system boundaries.

There are also commensalistic and symbiotic relationships among intertwined and interacting enterprise systems, meaning that they use and help each other, respectively, to survive. Furthermore, the meta-system and its enterprise systems not only collaborate, but also coevolve and cocreate each other as well.

We also emphasized the importance of a loosely centralized GASS that governs (not manages or rigidly controls) the overall design, deployment, and operation of the meta-system and prevents the meta-system from falling into chaos. The GASS also provides overall strategy (strategy architecture), policies, guidance, direction, and standard services that facilitate cooperative behaviors. Further, it supports the emergence of self-organizing behavior out of complex and chaotic situations.

For future research, it is recommended that the concepts of the GASS of meta-systems and the various degrees of autonomy of its component systems be examined and their governances also be studied. Additionally, the concept of the complex Autopoiesis SoS (self-production, where a whole exists for and is created by its parts and viceversa) can be used to further research and studies of meta-systems.

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