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Systems Research and the Quest for Scientific Systems Principles

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Abstract: Systems Research formally originated in the 1950s, but a scientific understanding of systemness is still nascent. This shortcoming produces significant risks for complex systems engineering and practice. Current "systems principles" are qualitative heuristics, and systems science is scientific more in attitude than because of any grounding in systems principles employing clear and quantifiable concepts. In this paper, I propose that a model of how principles and laws are understood across the specialized sciences can, when applied to systems science, open up new ways to discover systems principles. This approach has led to the identification of six new avenues for discovering systems principles. In this paper I explain one of these research avenues (which leverages the maturation profile of the specialized sciences) in detail, and reference active projects to pursue others. The research approach advocated in this paper has the potential to lead to a new perspective on the nature of and relationship between systems science and systems engineering.

Keywords: systems principles; General Systems Theory; GST; GST*; Systems Philosophy; General Systems Worldview; Scientific Realism; system patterns; design virtues

1. Introduction

In a recent work on Systems Research [1], Mary C. Edson & Gary Metcalf posed the question: "What factors or forces or phenomena create stable patterns of order out of a universe which is inherently malleable?". This can be viewed as a research question for addressing, from a systems perspective, an issue raised by Steven Weinberg, saying: "In all branches of science we try to discover generalizations about nature, and having discovered them we always ask why they are true. I don't mean why we believe they are true, but why they *are* true. Why is nature that way?" [2]. In this paper I argue that Systems Research focused on systems principles represents a common ground between researchers investigating such questions, and discuss challenges and opportunities for strengthening systems science and systems engineering via such Systems Research.

Systems Research involves two distinct though related concepts: doing research from a systems perspective, and doing research into the nature of systems [3] (p. 2). The origins of Systems Research can be traced back to the publication of Ludwig von Bertalanffy's seminal paper on open systems in 1950 [4], the formation of the Society for General Systems Research (SGSR) in 1956 [5] (p. 248) (see Endnote 1), and the publication of von Bertalanffy's book "General Systems Theory" in 1968 [6]. These events laid the foundation for a new scientific paradigm, in which the world is not seen as comprised of independent objects but understood as composed of entities whose properties and behavior depend on both their internal organization and ongoing interactions between them and their environment. This insight was seen as opening up a way to overcome the disciplinary fragmentation, social inequality, and existential risks of the (then) modern world [3] (p. 3), [7].

The systems paradigm has since become widespread in academia and industry, but the core problems that motivated the founders of the general systems movement have not been resolved, and in fact have become worse in many respects. Moreover, technology is creating an increasingly interconnected world, creating new challenges for stability, resilience, fairness, and viability. The social, socio-technical, and socio-ecological problems being identified for attention, and the projects being undertaken to address them, are increasingly complex and increasingly prone to underperformance, unintended consequences and even outright failure. Studies suggest the cost of IT project failures now exceed $100 B per year in the USA and €148 B per year in the European Union [8]. In the USA, the loss to the Federal Government due to systems engineering failures now exceed $73 B per year [9]. The cost of these failures lies not only in lost capital (which could have gone to other beneficial projects) but also a social cost in the delay, inadequacy or absence of the intended outcomes. In the UK, the government abandoned an IT project for integrating patient records in the National Health Service after spending £9.8 B on a project budgeted at £6.4 B [10], and in the USA the FBI abandoned a project for integrating case files after spending $100 M [8]. Big projects that do succeed typically show significant cost overruns, for example the Channel Tunnel and the Boston "Big Dig" both cost about double their original estimates.

In this paper, I argue that a contributing factor to the risks and failures faced in dealing with systemic complexity is that our scientific understanding of the intrinsic nature of complex systems, and consequently our ability to collect appropriate and relevant information when analyzing complex systemic scenarios, is still inadequate. I will analyze the nature of this inadequacy and present avenues of research that might help to overcome it. The proposed research activities would intrinsically be examples of Systems Research, and their outputs would enhance the potential of Systems Research as a valuable research approach.

2. Systems Research and the Nature of Systems

2.1. The Scope and Maturity of Systems Research's Resources

Systems Research as an activity draws, in addition to knowledge from the specialized science domains, on three kinds of knowledge about systems.

First, we have hundreds of systemic research methods for analyzing a problem situation and devising plans of action, for example Action Research, Systems Dynamics, Operational Research, Soft Systems Methodology, Critical Systems Thinking, etc. [11–13].

Second, the methods draw to various degrees on about a dozen scientific theories about specialized aspects of system organization and behavior: Control Theory, Network Theory, Hierarchy Theory, Communication Systems Theory, Living Systems Theory, etc. [14].

Third, Systems Research is guided by a set of about a dozen heuristic principles that represent the collective wisdom of the systems community about the general nature of systems. These have not been formalized, and many variants exist in the literature, but they show some overlap despite differences in how they are formulated. Examples of these principles include statements such as that "systems have properties their parts do not have by themselves", "systems both change their environment and adapt to it", and "systems may be parts in several wider containing systems": see e.g., [15] (pp. 17–30), [16] (pp. 33–38), [17] (pp. 60–71), [18] (pp. 99–105). These principles form guiding orientations and basic assumptions for conducting Systems Research, and are therefore part of the philosophical component ("Guidance Framework") of the transdisciplinary field of Systemology, as illustrated in Figure 1.

In relation to this generic map of the structure of a discipline, known as the "AKG Model" [19], Systems Research can be understood as part of the "Activity Scope" of Systemology, and the systemic methodologies and systems theories referred to earlier are part of the "Knowledge Base" of Systemology.

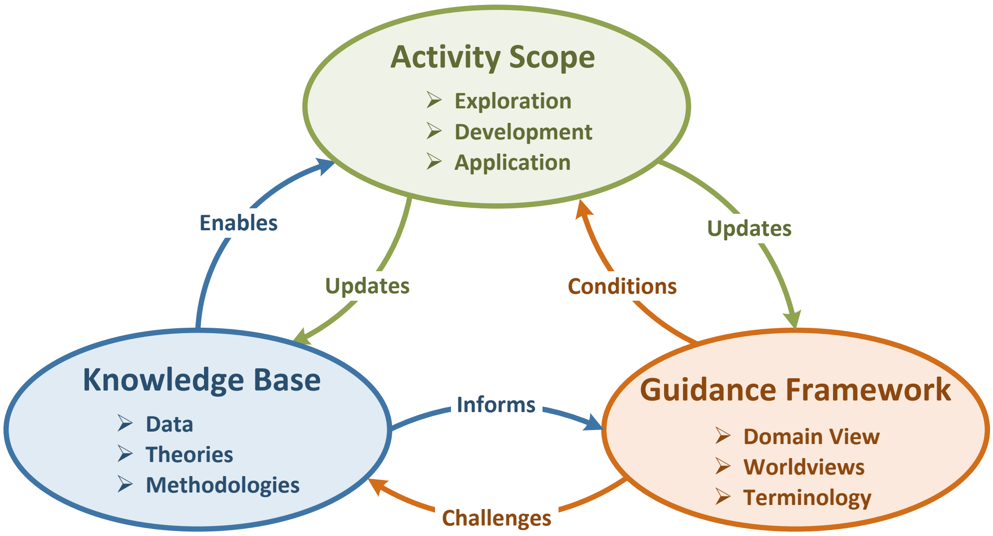

Figure 1. The AKG Model of a Discipline [19] (p. 23) (reproduced with permission).

In terms of the maturity of these components, there are a dozen or so robust scientific systems theories and these have been notably useful in systems engineering (e.g., Control Systems Theory and Network Theory). Systemic methodologies are plentiful (hundreds), and at least two dozen are widely used but their development has outpaced the development of systems theories and most are heuristically based and only weakly grounded in scientific systems theory [20] (p. 311). The systems principles in use are heuristically based and not standardized in terms of their scope and terminology. There are relatively few of them (about a dozen), and individual researchers maintain and develop their own versions (see Table 1 for a representative sampling).

The lack of development and maturity of the systems principles is a key handicap for Systems Research. To show this, I briefly explain the nature and function of principles in science in general and hence in systems science specifically.

2.2. The Nature and Significance of Principles

There are multiple terminologies and perspectives in science and in philosophy on the nature of principles, laws, theories and models. For present purposes, I will follow a perspective called Scientific Realism, which is presently the dominant view amongst metaphysicians of science [21] (p. 299), and is well matched to the working practice of practicing scientists. Briefly, Scientific Realism posits that a concrete world exists independently of our mental states, that the truth of our theories depend on the nature of the world, and that our best scientific theories are approximately true of the world (see Endnote 2). Within the framework of Scientific Realism, I will follow a model known as the "Principles-Laws-Theories" (PLT) model of modern science [22]. For present purposes, I will focus only on its notion of principles (I discuss the PLT model more broadly in [23,24]. The PLT model represents an early attempt (1996) in the modern resurgence of metaphysics to show how modern science depends on metaphysical principles and how such principles relate to scientific laws and scientific theories. The metaphysics of science has advanced rapidly in the last two decades, but in my view the basic structure of the PLT model is still the most practically useful framing we have of these relationships. Please note that terms such as 'principle' and 'law' have different meanings in different kinds of disciplines, as discussed in Endnote 3; it is important not to conflate these different uses.

Table 1. Examples of Sets of Heuristic Systems Principles.

Source	Lists of Systems Principles
H. Sillitto (2014). *Architecting Systems: Concepts, Principles and Practice* [16] (pp. 33–38) (note: this list has been included in the Systems Engineering Handbook 4th edition (2015) [25] (pp. 20–21))	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. 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. Types of system include technical, biological, social, ecological, environmental and any combination of these.
G. Mobus & M. Kalton, (2015), *Principles of Systems Science* [15] (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. 3. Systems are themselves, and can be represented abstractly as, networks of relations between components. 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
D. Hitchins (1992), *Putting Systems to Work* [17] (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 locally-stable 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.
P. Senge (1990), The Fifth Discipline [26] (pp. 57–67); reprinted in B. Lawson (2010), A Journey Through the Systems Landscape [27] (p. 70). [note: Senge calls these "laws", Lawson calls them "principles"]	1. Today's problems come from yesterday's solutions. 2. The harder you push, the harder the system pushes back. 3. Behavior grows better before it grows worse. 4. The easy way out usually leads back in. 5. The cure can be worse than the disease. 6. Faster is slower. 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.

In science, principles are the most fundamental assumptions we make about the nature of the world. They represent what we take to be true in general, and hence fulfill a number of orienting functions, including [22] (pp. 65–72):

(a) Encapsulating what is deemed ontologically or metaphysically possible or necessary (for example, the "Principle of Sufficient Reason" (which claims that effects have proportionate causes) is a presumption against the occurrence of miracles);
(b) Setting bounds of scientific forms of reasoning (for example the "Principle of the Uniformity of Nature" (which claims that the same causes always produce the same effects) supports reasoning from evidence to conclusions or predictions);
(c) Providing guidelines for doing science (for example the "Energy Conservation Principle" provides a way of checking that all the contributors to a given effect have been identified);
(d) Defining basic concepts (for example, Newton's so-called "Laws of Motion" are really not laws at all but refined definitions of the notion of a "force").

The principles are not independent claims but can overlap or reinforce each other. For example, the Principle of Sufficient Reason can be viewed as a corollary of the Principle of the Uniformity of Nature (or vice versa).

The principles of science are grounding assumptions and hence not provable by science. However, they are provisional and can be challenged and amended. Nevertheless, they are regarded as representing deep truths about the nature of the world, and their formulation and evolution is informed by progress in science. They express what we take to be the conditions for the possibility of the empirical phenomena observed by sentient beings. In this way, the principles of science represent the invisible reality underlying the phenomenal one, and form part of metaphysics rather than science. Taken together, the principles of science characterize the nature of Nature, so we might say that our image of the nature of Nature is the gestalt that reconciles the joint entailments of the principles (rather like the elephant image that reconciles the observations of the seven blind men). These relationships are illustrated in a simplified way in Figure 2. Changes in the principles can have dramatic consequences for the scientific paradigm, as for example occurred when the Newtonian notion of "mass" was redefined by Einstein's General Relativity theory.

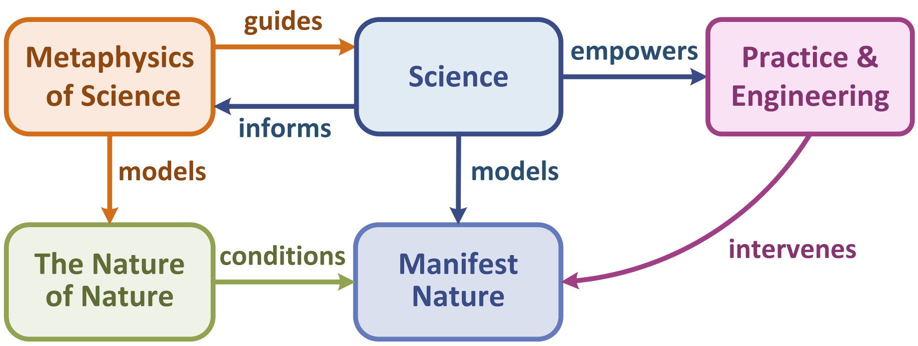

Figure 2. The Significance of Philosophy for Science and Practice/Engineering.

Principles generally start out as qualitative heuristics based on limited observations, and only later on (typically with great difficulty) become exact, quantifiable, and profound. For example, the (heuristic) Aristotelian notion of a force had been defined simply as a push or a pull, while the (scientific) notion from Newton (involving "inertia") was quantitative and carried profound implications, leading to the "Mechanical Revolution".

2.3. The Nature and Significance of Systems Principles

The content of Systems Science is distinct from that of the specialized sciences, but the structure of Systems science is likely to be no different from that of the rest of science. From this brief review we can thus form some idea of the scope and potential of systems principles. We can directly paraphrase the above discussion for the systems case as illustrated in Figure 3.

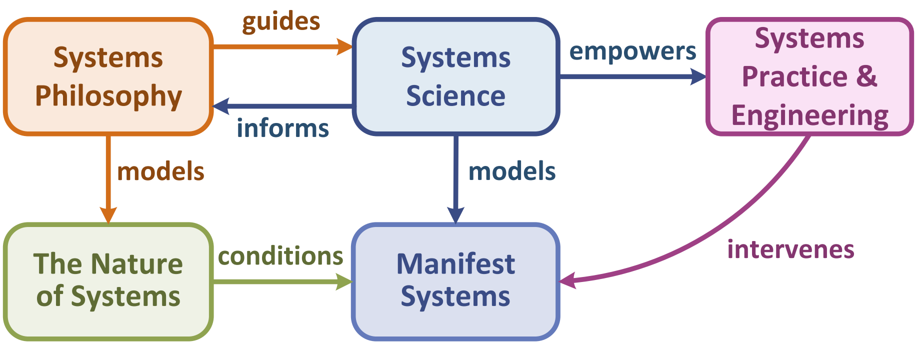

Figure 3. The Significance of Systems Philosophy for Systems Science and Systems Practice/Engineering.

The correspondence between these two diagrams lies in the observation that Systems Philosophy models the systemic nature of the nature of Nature, and Systems Science models the systemic nature of manifest systems. In Figure 3, the two modelling arrows and the intervention arrow involve Systems Research activities.

Paraphrasing what was said above about our image of Nature, we can now propose the following. Systems principles are the grounding assumptions of systems science, and hence not provable by systems science. However, they are provisional and can be challenged and amended. Nevertheless, they are regarded as representing deep truths about the systemic nature of the world, and their formulation and evolution is informed by progress in systems science. They express what we take to be the conditions for the possibility of the empirically systemic phenomena observed by systems thinkers. In this way, the systems principles represent the systemic nature of the invisible reality underlying the systemicity of the phenomenal one, and form part of systems philosophy rather than systems science. Taken together, the systems principles characterize the nature of systemness, so we might say that our image of the nature of "system" is the gestalt that reconciles the joint entailments of the systems principles. A set of coherent and scientific systems principles would form the core of a foundational general systems theory (designated GST* since 2015 [19,28]), and changes in the systems principles could have dramatic consequences for the systems worldview.

As with the principles of science, systems principles can be heuristic or scientific. At present, we have only or mostly heuristic systems principles, and they are not unified. One consequence has been a proliferation of "images" of what systemness entails: the *International Encyclopedia of Systems and Cybernetics* [14] devotes 18 pages to listing variations on the system concept found in the systems literature, and an ongoing Fellows Project in the International Council on Systems Engineering (INCOSE) has reviewed more than a hundred current and historical system definitions in an effort aimed at proposing one that is appropriate for contemporary systems engineering (personal communication from Hillary Sillitto, 22 November 2016). This variety is a clear indication of the incompleteness and immaturity of our present systems principles.

2.4. The Link between the Incompleteness of Systems Principles and Project Risks

In the light of an understanding that systems principles jointly characterize the nature of systems, and the incompleteness of the present set of systems principles, it is evident that our scientific understanding of the nature of complex systems is also incomplete and immature. From this we can easily see how some of the risks faced by complex systems projects derive from this shortcoming in our knowledge about the nature of systems.

For example, it has been argued that significant contributing factors to the failure or underperformance of complex system projects is a lack of methodologies for transferring knowledge and experience across project phases and between projects, and inadequate education in systems thinking [29–32]. However, adequately addressing such factors requires a general systems theory, in order to ground objectivity and completeness when capturing knowledge and experience relative to a system of interest, and when teaching students how to think about systemic scenarios.

It has also been argued that systems theories are increasingly inadequate for supporting complex systems design. Recent studies claim that the rising complexity of engineered systems has eroded systems engineers' ability to predict the outcome of design decisions [31], leaving them without a principled basis against which they can check unexpected system behavior [30]. A general systems theory, based on more complete and more scientific principles, would be helpful for identifying how the specialized aspects of systems, as represented in current systems theories, interoperate to produce system-level behaviors.

Establishing a scientific theory about the nature of systems is therefore arguably the key requirement for future success in complex systemic design, intervention and governance.

2.5. The Potential and Limits of of Heuristics

The argument developed here should not be taken as dismissive of the value of heuristic principles, or to denigrate the systems principles we have so far. Heuristic principles necessarily pre-date scientific ones, and they are articulated precisely because they have significant practical value [33]. As Sir Geoffrey Vickers noted, "Throughout almost the whole of human history, technology has progressed with an uncanny ignorance of the scientific principles which were guiding it" [34]. Technologies based on heuristic principles achieved astonishing sophistication even in ancient times. Well-known examples of high technological achievements pre-dating the scientific revolution include colloidal copper ceramic glazes (China, 10th century CE), crucible (wootz) steel (India, 3rd century CE), composite bows (Mongolia, 1700 BCE), geopolymers (Egypt, 2500 BCE), megalithic engineering (France 4700 BCE), and ultrafine polishing of corundum-rich stones (China, 6000 BCE).

The power of heuristics, however, creates two hazards. First, as John Warfield noted, "When technology leads, as in the computer age, it is inevitable that practices not embedded in scientific foundations will evolve to a status of dominance. When this occurs—and in fact it has—it is also inevitable that some time will elapse before these practices will give way to new practices founded in science" [35]. This is evident in the extent to which systems methodologies are multiplying while little attention is given to advancing the foundational scientific understanding of systemness.

Second, effective heuristic principles tend to limit the imaginations of scientists and technologists to human-scale phenomenology, so that for example control of fire led heuristically to technologies such as pottery, smoke-cured meats, baked bread, convective underfloor heating and gunpowder. All these applications fell under the broad idea of things changing due to the application of heat. However, once fire was understood scientifically in terms of chemistry and electromagnetism it opened routes to inventions unimaginable from thinking about fire phenomenologically, such as computers, lasers, mobile phones, heart pacemakers, micro-wave ovens, radio, MRI scanners, and radar astronomy.

The transition from craft-based technology to science-based technology happens when a way is found to transition from heuristic to scientific principles for grounding the approach to action. Principles characterize the nature of a phenomenon, so at the outset they are necessarily based on experiences, and hence we always start with qualitative rules of thumb (heuristics). To become scientific, the observations have to be framed in a way that is quantifiable and significant for scientific exploration. For example (returning to an example briefly mentioned before), the concept of a "force" was heuristically defined by Aristotle as a push or pull, meaning a force is what causes something to move. This followed naturally from observing donkeys pulling loaded carts, where the cart moved when the donkey pulled and stopped when the donkey did. The idea that forces cause motions was the dominant view of the nature of a force from Aristotle (ca. 350 BCE) to the time of the Galileo (1600 CE). This model, however, created many puzzles, such as why arrows carried on moving after departing the tensed bowstring, and what caused the planets' continuous motion. The scientific breakthrough was due to Newton, who introduced a new notion of a force as causing a change in the state of motion of an object, quantified as $F = m \times a$. This definition of a force was scientifically profound as it expressed the concept in relationships between exactly quantifiable concepts and carried many testable implications, hence opening the way for the "Mechanical Revolution". This example can easily be multiplied from the history of science, for example our contemporary scientific notion of the conservation of energy replaced Lucretius's heuristic principle (dating from ca. 75 BCE) that "nothing comes from nothing", and the scientific notion of relativistic space-time introduced by Einstein replaced the heuristic observation that everything that happens occurs at some time and at some location.

The great untapped potential of the systems perspective is evident in the observation that our best notion of systemness is pretty much still the phenomenological one we inherited from Aristotle, namely that the whole is more than the sum of the parts. Modern systems researchers have extended this via further heuristic principles, but these do not make profound conceptual shifts nor bring quantification and testable consequences, and although they paint a richer picture than Aristotle's notion they have also created a fragmentation of the systems concepts in use.

3. The Ongoing Quest to Find Scientific Systems Principles

3.1. The Challenge of Finding Scientific Systems Principles

The present lack of a cohesive and scientific perspective on the nature of systems within the systems community is *prima facie* surprising. The quest to establish a scientific understanding of the nature of systems started at least as far back as the 1930s with the calls by Ludwig von Bertalanffy [3] (p. 5) (see also Endnote 4). He campaigned for a general scientific understanding of systems, saying, "There exist models, principles, and laws that apply to generalized systems or their subclasses, irrespective of their particular kind, the nature of their component elements, and the relations or 'forces' between them. It seems legitimate to ask for a theory, not of systems of a more or less special kind, but of universal principles applying to systems in general. In this way, we come to postulate a new discipline, called General System Theory. Its subject matter is the formulation and derivation of those principles which are valid for 'systems' in general ... A first consequence of the existence of general system properties is the appearance of structural similarities or isomorphisms in different fields. There are correspondences in the principles that govern the behavior of entities that are, intrinsically, widely different" [36].

Von Bertalanffy held that General System Theory "is [the] scientific exploration of 'wholes' and 'wholeness'" [6].

The founding of the SGSR in 1956 should have given a great boost to the search for this scientific understanding, but the "formulation and derivation" of scientific systems principles has proved to be a major challenge for Systems Research. Much scientific work has been done to investigate the isomorphic systems patterns that were thought to signify the existence of systems principles [20,37–39], but little scientific progress has been made towards discovering these principles. In 2015 INCOSE identified "expanding the theoretical foundation for systems engineering" as one of its six imperatives for SE in the decade ahead [29], and in its *Systems Engineering Vision 2025* INCOSE echoed Bertalanffy's call to action from the 1950s, saying, "It is therefore important to develop a scientific foundation that helps us to understand the whole rather than just the parts, that focuses on the relationships among the parts and the emergent properties of the whole. This reflects a shift in emphasis from reductionism to holism. Systems Science seeks to provide a common vocabulary (ontology), *and general principles explaining the nature of complex systems*" [29] [emphasis added].

It seems extraordinary that the important quest for explanatory (rather than descriptive) principles should have made so little progress in more than half a century of effort. However, on closer inspection, two root causes can be identified.

First, the idea that there are systems principles, and that it would be valuable to know them, does not suggest avenues for their discovery. Although the existence of principles is inferred from the existence of isomorphic systems patterns, the relationship is probably not ever one-to-one, and knowing more isomorphisms only increases confidence in the existence of principles without making them easier to find.

Second, right from the outset there has been a diversity of views about just what is meant by terms such as "system", "systems principles", and "general systems theory", creating disarray amongst researchers looking for ways to advance the foundations of Systems Research.

In the works of von Bertalanffy alone, 16 different meanings of "GST" can be found [19] (p. 19), and as noted above, more than 100 system definitions can be found in the systems literature. Conceptual diversity has been widely valued in the systems community as an antidote to intellectual hegemony in a nascent disciplinary field, but it also hindered development of a coherent program for discovering scientific systems principles and finding a generally useful system concept, and it undermined the credibility of the field as a scientific discipline. This has in turn resulted in a decline in academic support for the development and teaching of systems theory.

3.2. Renewed Optimism about Discovering Scientific Systems Principles

Recently, a concerted effort was launched to identify a coherent framework of terms, concepts and perspectives which could underpin a structured collaborative effort to develop a general theory of systemness and make it the basis of a practical scientific transdiscipline [28,40]. This is a joint project of the ISSS and the INCOSE Systems Science Working Group, and supported by the International Federation for Systems Research (IFSR) and the Bertalanffy Center for the Study of Systems Science (BCSSS). The project is called the "General Systems Transdisciplinarity" (GSTD) Project [40], and the core team is David Rousseau, Jennifer Wilby, Julie Billingham and Stefan Blachfellner. Substantial progress has been made and published [19,41–46].

The insights, clarifications and models provided by this project have provided key insights towards a research framework for General Systems Research, and on this basis six avenues of research that might deliver scientific systems principles have been identified. One has been the subject of a pilot project in 2016 and this yielded three scientific systems principles that have been accepted for publication in early 2017 [24]. A second avenue of research will be outlined below and is planned to be the subject of a project commencing mid-2017, which will include an associated conference in 2018. Other research avenues are mentioned in Endnote 5.

The proposal presented below builds on a recent GSTD study published in 2016 as "In Search of GST" [41] (hereafter "*GSTSearch*") (This is an open-access article that can be downloaded from http://www.systema-journal.org/issue/view/47). This study found that if we look at how disciplines evolve then a general pattern can be observed, and it proposed various ways in which this pattern could be used, e.g., as an outline of the structure of Systemology, as a framework for organising the present body of systems knowledge, for building a maturity model of Systemology, for identifying key gaps in the Systemology knowledge base, and for better understanding the scope and role of GST* within Systemology. Two of these proposals have already been adopted as new projects, as described in Endnote 6. In the present paper I propose a further use for this pattern as suggesting how collaboration between the specialised disciplines can to help identify and refine scientific systems principles.

4. A Strategy for Discovering Scientific Systems Principles via the Domain Sciences

4.1. Brief Overview of the Disciplinary Maturaration Profile Presented in "GSTSearch"

In *GSTSearch* it was argued that as disciplines mature they are able to answer increasingly difficult questions about their subject matter, and give increasingly sophisticated explanations of its properties. These questions range from precursor questions that set the stage for explanatory research, through ones about specialized aspects of the subject matter, and on to ones of general relevance for the subject area. Briefly, the questions are:

1. What qualifies as a subject for the discipline?
2. What concepts are needed to describe the subject entities?
3. What is the scope of the discipline's enquiry?
4. What are subject entities like?
5. How do they work?
6. Why are they like this? (note this is not a teleological question, see Endnote 7)

Question 6 can be subdivided into several subsidiary questions, as follows:

6.1. How do the simplest individuals come about?
6.2. How do complex individuals come about?
6.3. How does the variety of complex individuals come about?
6.4. Why are subject entities like this? Why do they work as they do? Why do we have *these* kinds of entities rather than others?

Answers to questions 1–3 involve identifying criteria for drawing the discipline's technical boundaries (Q1), terminological boundaries (Q3), and philosophical boundaries (Q3). Answers to Q4 generate data that describe and classify the subject entities and associated phenomena. Answering Q5 onward generates explanatory theories. Theories answering Q5 constitute the specialized theories of the discipline, and are concerned with the processes that produce or maintain the specific features and functions of the subject entities. Theories answering Q6 are general theories for the discipline, concerning processes that condition all the subject matter entities.

Questions 1–6.4 can be addressed concurrently, but they are interdependent in the sense that progress with any "later" one depends strongly on the progress already made with "earlier" ones. However, answers at any level can have revisionary implications for "lower-level" ones, resulting in revisionary cycles within the system of knowledge that can have consequences across all levels.

Overall, this list of questions indicates how the knowledge base of a discipline becomes more complex and more sophisticated as it matures, and that 6.4 is the last one to become possible to address effectively. As disciplines mature, they naturally arrive at this question. As Steven Weinberg put it, "In all branches of science we try to discover generalizations about nature, and having discovered them we always ask why they are true. I don't mean why we believe they are true, but why they *are* true. Why is nature that way?" [2].

4.2. Interpreting the Maturation Profile in Systems Terms

I will now characterize this 'maturation profile' from a systems perspective. In the systems worldview, everything is a system or part of one, and every kind of thing is a kind of system (apart from ultimate "atoms", if there are such). Every specialized scientific discipline can therefore be regarded as studying some category of system. These system kinds can be arranged in a hierarchy of 'levels' of increasing complexity, with each level having an associated area of specialized scientific study. This complexity hierarchy has evolved in a sequential manner, showing that the emergence of more complex systems is facilitated by the prior existence of simpler systems, as illustrated in Figure 4.

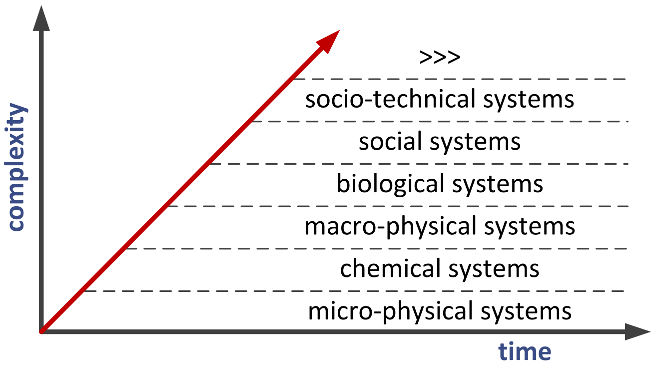

Figure 4. The Evolution of a Hierarchy of Complex Naturalistic Systems over Time.

From a system perspective we can note that the answers disciplines develop in response to each of the kinds of questions listed above are conceptual systems of relevant kinds. In Table 2, these kinds are identified in a simplified way. The scope of each is discussed in detail in *GSTSearch* [41].

Table 2. Cumulative Development of Knowledge Reflected in Kinds of Systems Models.

#	Question	Systems Models
1	What qualifies something as a subject entity?	Complexity Models
2	How can we describe subject entities?	Ontological Models
3	What limits the enquiry scope?	Worldview Models
4	What are the subject entities like?	Morphological Models
5	How do they work?	Mechanismic Models
6	Why are they like this?	(see #s 6.1–6.4 below)
6.1	How do the simplest individuals come about?	Generative Models
6.2	How do complex individuals come about?	Developmental Models
6.3	How does the variety of individuals come about?	Evolutionary Models
6.4	Why do we have the specific variety we encounter?	Optimization Models

I propose that the progression identified in Table 2 be called the "Disciplinary Maturation ("DMAT") Model. Although answering the "maturation questions" involves building systems models at every stage, it is evident that as the progression unfolds the mode of thinking within the discipline becomes more systemic in the sense of "systemic" as understood within the general systems community, i.e., researchers become more sensitized to the significance of relationships, organization, context and the interplay between objectivity and subjectivity, and this is increasingly reflected in the research questions being proposed and in the systems models being developed. This systemic sensitivity typically becomes overt when a discipline engages with Q6, and especially Q6.4. At this stage we see the emergence of "systems versions" of the specialized disciplines, e.g., Systems Geology, Systems Biology, Systems Psychology, Systems Medicine, Systems Ecology and so on. At this point the specialized disciplines also become more interdisciplinary, as explanatory models begin to explore the *systemizing* processes (ones that produce systems) that run across the boundaries' of the complexity hierarchy, rather than being so closely focused on the *systemic* processes that sustain the properties of systems belonging to the complexity level of the discipline.

4.3. Discussion and Proposal

The engagement with Q6.4 is specifically relevant for the subject of this paper, in the following way. Q6.4 arises once we have models of how specific functions in the subject entities are performed by structures and processes. These models (which represent answers to Q5–Q6.3) can be viewed as collectively representing "system designs", with the caveat that use of the term "design" when referring to features of natural systems does not entail the existence of an "designer" in the sense of an agent with intentionality. In terms of designs Q6.4 can then be paraphrased as, "why do the subject entities exhibit the designs that they do?" This a puzzle because in general similar functions can be performed by a range of different designs, so an explanation is needed for why certain designs do not arise or persist, and how the ones that do arise or persist are "selected" from the larger "possibility space". The answer appears to have two aspects, one to do with optimization and one to do with innovation. First, the enduring designs appear to be ones that are optimized across 'design virtues' such as effectiveness, robustness, economy, modularity, resilience and so on, so part of the research here is focused on identifying the specific "design virtues" that "good" designs are optimized over, and showing how they support viability (for example, modularity might facilitate robustness or maintainability). Second, there must be constraints on natural processes such that virtuous designs are possible in principle and likely to arise in reality. This second aspect is addressed by the systems versions of the specialized disciplines as a search for "organizing principles" or "design principles" (e.g., [47–50]). These specialized disciplines are seeking solutions to their own disciplinary puzzles, and will express principles they identify in their respective disciplinary languages. However, the subject matter is general, as the way in which nature innovates must be common across the levels of the complexity hierarchy, so that new kinds of systems can continue to arise via interactions between and integrations across existing ones. This generality means that these design principles are nothing other than the general systems principles discussed in the first part of this paper, although perhaps interpreted from specialized disciplinary perspectives.

The search for these design principles in science is matched by a need in systems engineering and management science for design principles to guide systems architects towards designs that are optimized across design virtues that mirror nature's ones. In the absence of such scientific knowledge we have seen the emergence of heuristically based principles such as those shown in Table 1, and heuristically based virtue criteria such as those now emerging in "value-driven systems engineering" [51].

In the light of the above discussion we can now propose that there is an emerging opportunity to identify scientific systems principles by comparing and combining the work on design principles being done by researchers working at the leading edge of the more mature disciplines. By bringing these researchers into conversation and collaboration, it may be possible to find ways to generalize the way in which the principles being discovered are formulated, and so make them transferable across disciplinary boundaries. These transdisciplinary scientific systems principles will benefit not only those disciplines already looking for design principles but also help to accelerate the maturation of younger disciplines by removing the need for independent discovery, and by sensitizing them to aspects of their subject systems they might not otherwise realize are involved in the properties they study.

The development of this area is likely to change our perception of the nature of systems science and systems engineering. It was observed earlier that answering Q6.4 involves two aspects: innovation and optimization. The systems principles and design virtues involved are general and transdisciplinary. As such they do not 'belong' to the specialized sciences but are part of General Systemology, and this in turn is part of the theoretical foundations of Systems Engineering. In this light we can now suggest something a mature General Systemology and mature Systems Engineering would add to the domain sciences and specialized engineering disciplines: General Systemology would be the science of systemic innovation and optimization, and Systems Engineering the practice of realizing optimized systemic innovations (for comparison see a current definition in Endnote 8). Making General Systemology and Systems Engineering more scientific in this way is naturally a common project of the specialized sciences and systems researchers, and achieving it will benefit people, societies and ecologies by reducing the risks currently attaching to complex projects.

5. Endnotes

1. The SGSR was renamed in 1988 to the International Society for the Systems Sciences (ISSS).
2. Useful discussions of Scientific Realism can be found in [21,52,53]. Within the present systems movement it is related to the view called Critical Realism [54,55]. As a worldview component it is close to the view of the founders of the general systems movement, known as the General Systems Worldview, about which see [45]. Scientific Realism encompasses three commitments, which can be briefly stated as (a) that the world has a definite and mind-independent structure, (b) that scientific theories are true or not because of the way the world is, and (c) that our best scientific theories are approximately true of the world. Although Scientific Realism has widespread support amongst contemporary metaphysicians of science it is important to note this is not a uniform position, for example when thinking about the world's "structure" some Scientific Realist are Atomists (who think that only fundamental particles are really "things"), some are Priority Monists (who think that only one thing exists, namely the whole universe) and some are Compositional Pluralists (who think parts can make up new kinds of things and things can have some properties not determined by their contexts). There are further divisions within these views, and Scientific Realists also differ from each other about other issues such as the nature of laws, causation, necessity etc. Moreover, all these positions can be reformulated in terms of thinking primarily about things, or processes, or interplays of things and processes.
3. It is important to distinguish between the uses of terms such as "principle" and "law" in science and their uses in other domains such as ethics and mathematics. In science, a principle represents a general assumption about the nature of nature, whereas in moral philosophy a principle is typically taken to be an unconditional (but defeasible) obligation on free agents. Likewise in science, a "law" expresses a consistent proportionality between objectively observable specific occurrences, whereas in jurisprudence a "law" represents a socially constructed agreement about how free agents ought to act in anticipated circumstances. Moreover, in science the principles and laws have to be mutually consistent, but under certain circumstances moral principles can be mutually incompatible or in conflict with moral laws. Similar distinctions apply regarding other relevant concepts such as "truth" and "proof". Note that in the history of science, the required consistency between principles and laws have led to the distinction between them not always being correctly applied, so that what are principles are sometimes referred to as laws or vice versa.
4. In many ways, von Bertalanffy's work in Austria and America duplicated the earlier work of Bogdanov in Russia [56], but there is no evidence that von Bertalanffy knew about Bogdanov's work, and it was von Bertalanffy's work that proved influential in the West. For reviews of Bogdanov's work, see [57–59].
5. In Section 3.2 above it was mentioned that insights from the GSTD project suggested keys for a General Systems Research Framework from which so far six avenues of research towards scientific systems principles (SSPs) have been identified. Briefly, they are:

    a. Apply scientific principles to systems concepts (a pilot project based on this idea has produced positive results [24]);
    b. Collect design principles from maturing specialized disciplines and generalize them (as discussed in this paper and proposed for a collaborative project in 2017/18 and linked to the 2018 ISSS Conference);
    c. Distil principles from metaphysical tenets in the general systems worldview;
    d. Formulate principles by generalizing from systems laws;
    e. Apply systems science to heuristic systems principles;
    f. Collate system definitions and convergently develop one by distilling systems principles as the criteria that must be jointly satisfied by the system "image".

These six avenues supplement the historical one suggesting principles can be found by abstracting from isomorphic system patterns.

6. Two of these proposals have already been adopted as new projects. First, following on from the 2016 IFSR "Conversation" in Linz Austria (April 2016) and its follow-up at the ISSS meeting in Boulder, CA, USA in July 2016, the IFSR initiated a project to develop a maturity model of Systemology based on this framework, to be led by Mary C. Edson and David Rousseau; Second, at INCOSE's 2017 International Workshops (IW'17) in Los Angeles, CA, USA, the INCOSE SSWG, chaired by James Martin, will be holding a workshop, led by Tim Ferris, to explore the viability of classifying the content of INCOSE's Systems Science Body of Knowledge (SSBoK) by using this framework.
7. In science, this "why?" is not a teleological question (i.e., it does not presuppose an intent or purpose behind the phenomenon), but is aimed at addressing the legitimate scientific question of how it happened that things of this kind arose in Nature, and how it is that these kinds of things arose rather than other ones.
8. This view of Systems Engineering would be more specific than, but not a departure from, the current definition of Systems Engineering as "an interdisciplinary approach and means to enable the realization of successful systems" [25] (p. 11).

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