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On the Architecture of Systemology and the Typology of Its Principles

David Rousseau [1,2,3,4]

[1] Centre for Systems Philosophy, Surrey KTI5 1EL, UK; david.rousseau@systemsphilosophy.org; Tel.: +44-(0)-7714-677-687
[2] Centre for Systems Studies, University of Hull, Kingston-on-Hull HU6 7RX, UK
[3] Alister Hardy Research Centre, University of Wales TSD, Lampeter SA48 7ED, UK
[4] Bertalanffy Center for the Study of Systems Science, 1040 Vienna, Austria

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Abstract: Systems engineering is increasingly challenged by the rising complexity of projects undertaken, resulting in increases in costs, failure rates, and negative unintended consequences. This has resulted in calls for more scientific principles to underpin the methods of systems engineering. In this paper, it is argued that our ability to improve systems Engineering's methods depends on making the principles of systemology, of which systems engineering is a part, more diverse and more scientific. An architecture for systemology is introduced, which shows how the principles of systemology arise from interdependent processes spanning multiple disciplinary fields, and on this basis a typology is introduced, which can be used to classify systems principles and systems methods. This framework, consisting of an architecture and a typology, can be used to survey and classify the principles and methods currently in use in systemology, map vocabularies referring to them, identify key gaps, and expose opportunities for further development. It may, thus, serve as a tool for coordinating collaborative work towards advancing the scope and depth of systemology.

Keywords: systems philosophy; heuristic systems principles; scientific systems principles; general systems principles; specialized systems principles; general systems theory; GST

1. Systemology: Its Rise and Challenges

Over the last few decades the systems paradigm has become ubiquitous in academia and society, and the major fields of academic endeavour (philosophy, science, engineering, and practice) have each developed a nascent systemic specialisation (systems philosophy, systems science, systems engineering, and systems practice). However, the unified systems discipline we would call "systemology" is not yet established as such in academia[1]. The main reason for this lack of coherence is that systems *science* is still very young, and has no unifying general theory of systems. This has left systems engineering and

[1] The term "Systemology" was coined by Russ Ackoff ([1], p. 669), and recently promoted by Pouvreau and Drack as an apt translation of the German term, Systemlehre, meaning "an organized body of knowledge about systems" ([2], pp. 282–283). The term Systemlehre was introduced by Ludwig von Bertalanffy in the 1940s. He translated Systemlehre in 1950 as "Systems Theory" and hence his term Allgemeine Systemlehre as "General System Theory" [3], but this was an unfortunate translation choice, as shown by his proposal in 1972 to describe "General System Theory" as embracing "systems science", "systems technology" and "systems philosophy", ([4] pp. xix–xxiii). The term "Systemology" is now being widely adopted, e.g., [5–8], and "General Systemology" has been proposed as a better translation of von Bertalanffy's term "General System Theory" [2].

systems practice[2] dependent on largely heuristic systems principles. As will be discussed below, the need for fundamental progress in systems science is now acute but, happily, such research is now gaining momentum. To support this contemporary research effort this paper presents an architecture for systemology that can be used to understand how the components of systemology depend on, and reinforce, each other, and on this basis proposes a typology for classifying the principles each inherits or produces. It is hoped that this will inspire collaboration and aid co-ordination across the facets of the systems community, and so help to accelerate scientific progress in the maturation of systemology.

2. The Need for a Stronger Systems Science

The systems we would seek to build, govern or nurture are rapidly rising in complexity, and the associated projects are increasingly prone to underperformance, negative unintended consequences and even outright failure. Major US defence systems projects typically overrun by about 50% [9] and large civil systems projects often overrun by 200% or more [10]. Two thirds of big IT projects fail, and more than half of those that are completed under-deliver on their promised value [11]. The global cost of these failures and shortcomings is very large. In the USA, the cost of systems engineering failures now exceeds $73 billion per annum [12], and the global cost of IT project failures is now estimated at more $3 trillion per annum [13]. Individual projects can fail even after very large investments: a recent US IT system project was abandoned after a spending of $100 million [14], and a recent UK IT system project was abandoned after a spending of £9.8 billion [15].

One response to these challenges has been renewed calls for advances in systems science, to more powerfully support the methods of systems engineering (SE) and systems practice. Such calls have recently been made in many stakeholder organizations, including the National Science Foundation (NSF), the International Council on Systems Engineering (INCOSE), the International Federation for Systems Research (IFSR), and the International Society for the Systems Sciences (ISSS) [16–19].

This call for advances in systems science has triggered renewed interest in systems principles and further calls for enriching the heuristic principles in current practice with more scientific ones. For example INCOSE, in their "Systems Engineering Vision 2025", said:

> "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". [17]

This reiterates an earlier call by Ludwig von Bertalanffy, one of the founders of the ISSS, for the development of a general theory of systems, saying:

> "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". [20]

These calls have stimulated recent debate about the nature, role and developmental status of systems principles, and this paper is a contribution to that discussion. In particular, I will here

[2] The term "Systems Practice" refers to a professional activity involving the application of "Systems Thinking" to address a problem or pursue an opportunity, typically (but not necessarily) in the context of management science. Systems Thinking is a form of analysis and synthesis that emphasizes systems concepts such as stakeholder, hierarchy, emergence, feedback and boundary. Systems thinking can enter into any phase of a project, e.g., problem structuring, research, design or intervention, but systems practice is the application of systems thinking for the purposes of staging an intervention. In this way Systems Practice involves the selection, deployment and operation of a systemic solution to a given issue. This may (or might not) involve the use of technological products.

argue that these questions should be addressed in the light of how principles are understood, used and discovered in general, rather than exclusively building on the ideas of the founders of the systems traditions.

3. What Are Systems Principles?

In general, a "principle" is a fundamental idea or rule that can provide guidance for making a judgement or taking action. Principles can take the form of injunctions, beliefs, concepts, assumptions or insights. Principles can range from fully heuristic ones (distilled from experience, intuition, belief or convention) to fully scientific ones (distilled from scientific theories or models). Principles are encountered in every sphere of human activity, so we have, e.g., principles relevant to ethics, aesthetics, economics, politics, science, engineering, agriculture, etc.

Examples of principles include the heuristic principle "do as you would be done by" and the scientific principle that "energy is conserved in all causal interactions". Historically, principles start out as heuristics, and over time some become more scientific, e.g., Lucretius's heuristic principle from 75 BCE that "nothing can come from nothing (or go to nothing)" is today the scientific principle that "energy cannot be created or destroyed but only transferred or transformed". As principles become more scientific, they become more useful for making apt judgements or taking effective action.

By "more scientific" principles we mean principles that more strongly reflect the scientific approach, that is, using clear and precise concepts, expressing qualities and relationships that can be subject to measurement, quantification, empirical verification or falsification, and so on. In this sense scientific principles can arise in philosophy, science, engineering, and operational/service contexts. The scientific enterprise can be viewed as aimed at making principles across these domains increasingly scientific.

Note that we make a distinction between "scientific principles" in the sense just explained and "science principles", i.e., the principles underpinning science.

Both heuristic and scientific principles can be either general (applying universally, e.g., conservation of energy) or specialised (applying only in specific contexts, e.g., the principles of disease prevention), as illustrated in a simplified way in Figure 1 with example principles.

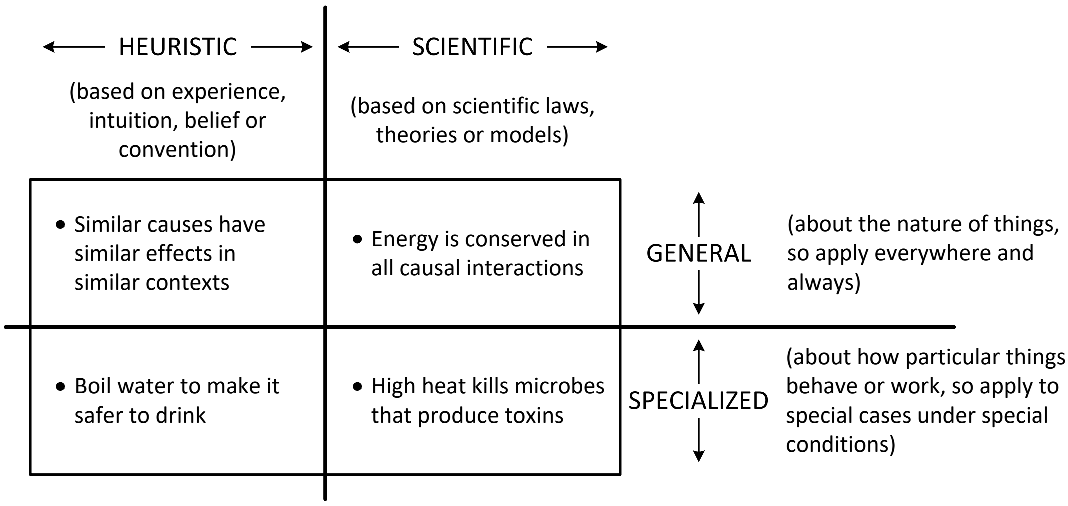

Figure 1. Relationships between forms of principles.

The effectiveness of science depends on having strong principles underpinning scientific research methods at a fundamental level (e.g., the general principles that energy is always conserved or that effects have sufficient causes) enabling scientific activities to discover specialized laws of nature (e.g., Boyle's Law that states the balancing relationship between pressure and volume in an ideal gas) and to reveal strong explanatory principles (e.g., that infections are caused by microbes).

From this understanding of the nature of principles we can now say that *systems* principles are fundamental rules, beliefs, ideas or insights about the nature or workings of systems, and hence systems principles guide judgment and action in systemic contexts. In the case of systems science the search for scientific systems principles (SSPs), and in particular *general* SSPs will be subject to the same considerations that apply to principles in general, as outlined above.

4. Status of Systems Science

The nature and roles of principles as articulated above explains why the calls being made for advances in systems science are framed in terms of establishing more scientific systems principles. Without strong scientific principles reinforcing systems science it cannot be effective in explaining the failures of systemic methods or in uncovering profound insights about the nature and workings of systems.

The present situation is far from ideal. We currently have hundreds of methodologies for systems practice (e.g., SSM, VSM, systems dynamics, CSTP, systemic intervention, etc.) and likewise for systems engineering (e.g., IBM Rational Harmony for SE, OOSEM, JPL-SA, SYSMOD, Vitech MBSEM, etc.), but typically these are only weakly grounded in scientific systems theories. We presently have only a dozen or so scientific systems theories (e.g., control theory, network theory, hierarchy theory, complexity theory, theory of dissipative structures etc.). We have no established general theory of systems, and when it comes to *general* systems principles we have only about a dozen or so heuristic rules (see e.g., ([21], pp. 60–71), ([22], pp. 17–30), ([23], pp. 20–21)[3] and a small handful of general concepts (e.g., wholeness, part, equifinality, closed and open system, etc. (see, e.g., ([31], pp. 91, 95)[4]. These concepts are still far from settled, including even the concept of "system" [39]. Three general scientific systems principles have recently been proposed [40] but they have yet to be formalized, and initial projects to evaluate them are still in process [41].

To fully appreciate the nature and scope of the scientific systems principles we are looking for it is necessary first to consider the nature and scope of system science, with a view to understanding how principles both underpin and flow from systems science, and second to consider how systems science and its principles relate to the other facets of systemology (systems philosophy, systems engineering, and systems practice) and their respective principles.

5. The Nature and Scope of Systems Science

A starting point for thinking about systems science is the view that every concrete thing is a system or part of one, and that natural systems can be arranged into a "complexity hierarchy", in which the "levels" represent increasingly complex systems that embed systems from the "lower" levels, and every level corresponds to some kind of system, as shown in a simplified way in Figure 2. A version of this perspective already occurs in Aristotle, but there is now an extensive modern literature on this, e.g., [42,43], and, notably, in the specific context of general systems theory, a seminal paper by Kenneth Boulding [44].

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3 It should be noted that systemists have published many statements under the rubric of "general systems principles" or "general systems laws" without these statements being actually useful for making judgements or taking action. These typically are just witticisms or platitudes about systems, such as "today's problems come from yesterday's solutions" (Senge), or "complex systems exhibit unexpected behaviour" (Gall). See, e.g., [24–26]. Others have published principles that are useful but not general, notably [27], which lists principles for specific contexts such as architecting, design, social systems, and political processes. For summaries of other specialised principles, see also [28–30].

4 There are very many concepts relevant to systems in the vocabulary of Systemology, e.g., there are 3807 entries in the second edition of Charles Francois' International Encyclopedia of Systems and Cybernetics [32]. These terms are far from standardised, and hence many systemologists have produced their own lists, e.g., [33], ([34], pp. 21–33), ([35], pp. 11–46), [36], ([37], pp. 13–68), ([38], pp. 353–360). However, very few of these concepts are general systems concepts, i.e., concepts describing universal attributes of systems as systems.

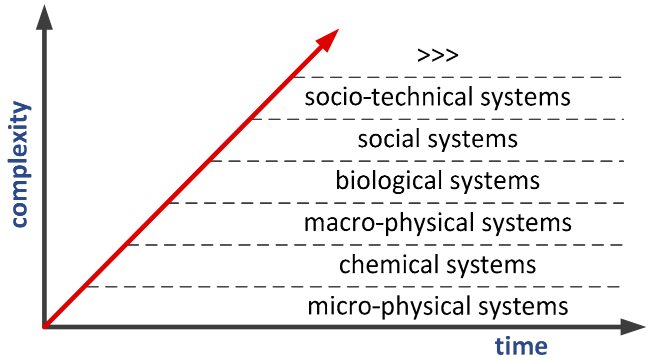

Figure 2. The levels hierarchy and its emergence over time (reproduced from [45], with permission).

The system levels in the complexity hierarchy correspond to the subjects of concern of the mainstream specialised scientific disciplines, so it can be said that every specialised scientific discipline studies some kind of system. Note, however, that this does not make these disciplines systems sciences, since it is only trivially true that their subjects are systems. These specialised disciplines do not have as their subject matter systems *as systems* but, rather, they seek to understand instances of kinds of systems.

The idea of a science of systems arises from three reflections on the complexity hierarchy:

i. First, given that systems occur on every level of the complexity hierarchy, a science of systems must be about what is true of or possible for systems across all the levels. This is the insight behind the claim that system science will be a transdiscipline, having relevance across the disciplinary spectrum, and will comprise theories that are scale-free and composition-independent. At a minimum, such a science must involve concepts and principles that allow systems to be characterised as a category of analysis distinct from things that are not systems, to enable instances of systems to be identified in the real world, and to explain/predict the behaviour and potential of systems as systems. Our present notions of "systemhood" are far from settled, but there is a rich literature on the subject [3,46–49] (see also footnote 3) and important efforts are under way to consolidate these ideas [39,50].
ii. Second, when looking across the levels we find similar patterns recurring across multiple levels, e.g., spiral forms in certain tropical storms, sea shells, flowers, and galaxies. Other examples include Fibonacci sequences and Zipf's Law regularities in natural phenomena [51–53]. Speaking metaphorically, these patterns represent solutions to design problems that systems must solve in order to create enduring complex structures. The existence of these isomorphically-recurring patterns across changes in scale and composition entails that there must be transdisciplinary specialised systems principles reflecting the nature of these "solutions". In principle each of these patterns can be "decoded" to establish a theory that explains the nature and function of the observed pattern, and to identify the relevant explanatory principles. Each such theory would then be a specialised systems science theory, and we have several of these already (e.g., control theory, hierarchy theory, network theory, communication systems theory, theory of dissipative structures, etc.). There are still many patterns in nature we do not theoretically understand, for example patterns of overlapping Fibonacci spirals, and Zipf's Law patterns. Moreover it is likely that there are further patterns we have not yet identified.
iii. Third, the isomorphically-recurring patterns arise independently in multiple contexts involving different scales, compositions, and developmental histories. This suggests that there are general systems principles that provide for the possibility of the *emergence* of these systemic patterns across contexts. Speaking loosely, these would be general principles about how Nature "finds" solutions, rather than (as above) specialised principles about how specific kinds of solutions

work. We have very limited knowledge of such general systems principles[5], but, in principle, they hold the promise of a general theory of systems that would explain both the emergence of specialized patterns and the relationships between them. Such a "general systems theory" (GST) would be very valuable not only for unifying the body of specialised systems knowledge but also for opening up new routes to discovery, just as Mendeleev's periodic table of elements did for Chemistry and Darwin's theory of natural selection did for biology.

From this we can infer that the theoretical aspect of systems science minimally comprises a set of concepts used to characterise the universal attributes of systems as systems, a database of isomorphic systems patterns[6], specialised systems theories that explain the mechanisms underpinning specific isomorphic systems patterns, and a general theory of systems that explain how the universal system attributes arise in nature and how they support the emergence of the isomorphic system patterns. The insights entailed by these concepts and explanations are the general and specialised principles of systems science. In addition systems science also includes the hybrid theories where systems principles are used or derived in the study or modelling of specialised kinds of systems, e.g., systems biology, systems ecology, systems psychology, systems economics, and so on.

We can now paraphrase Figure 1 for the case of *systems* principles, as illustrated in Figure 3. In the light of this four-fold classification system it is evident that that we know some general heuristic systems principles, many specialised heuristic principles, a small but respectable collection of specialised systems principles, and are almost entirely lacking in general scientific systems principles. This pattern of available principles of course reflects both the experiential richness and the theoretical immaturity of our knowledge of systems.

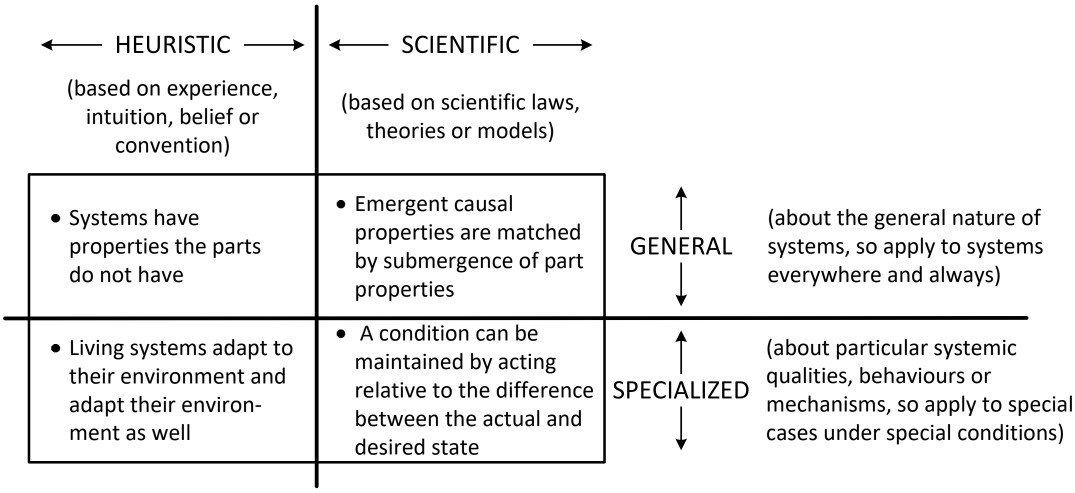

Figure 3. Relationships between forms of systems principles.

As the following discussion will make clear, developing the principles and theories of systems science will require the combined efforts of systems philosophers, systems scientists, systems engineers, and systems practitioners. To explain this, I will start by looking at the general structure of disciplines and disciplinary fields. To keep the presentation concise I will gloss over some nuances and details but, in my view, this does not distort the models being developed, and having been pointed out can

[5] Early work on general systems principles focused largely on general concepts (e.g., ([31], pp. 91, 95)), and while these remain controversial, important progress is now being made (e.g., [39]). In addition, progress is now being made towards establishing propositional general scientific systems principles. Two recent papers respectively presented three such principles [40] and eight strategies for discovery projects [54].

[6] Len Troncale and colleagues have over 40 years made an important contribution to the development of such a database of systemic isomorphisms, and extended this by also analysing the linkages between isomorphisms [51–53,55,56].

safely await elaboration at a later time. Moreover, the focus will be on disciplines that are, or aspire to be, scientific, and I will not here attempt to adequately reflect other kinds of disciplines. However, by focusing on disciplines that are or try to be scientific in their approach we can include consideration of disciplines from various branches of philosophy and practice, in addition to those from ("hard") science and engineering.

6. The General Architecture of Disciplinary Fields

For present purposes I will use the term "scientific endeavour" to refer to the typical activity sequence of disciplines that are or try to be scientific in their approach.

In general we can view scientific endeavours as motivated by some perceived personal or social problem, challenge, concern, opportunity or interest, and aimed at resolving, mitigating or satisficing that issue. The activities that underpin such endeavours come in several kinds, which form a general pattern of stages as illustrated in Figure 4. We can view this as the stages or phases of a typical project. For each of the stages I indicated terms often used to characterize the activities of that stage.

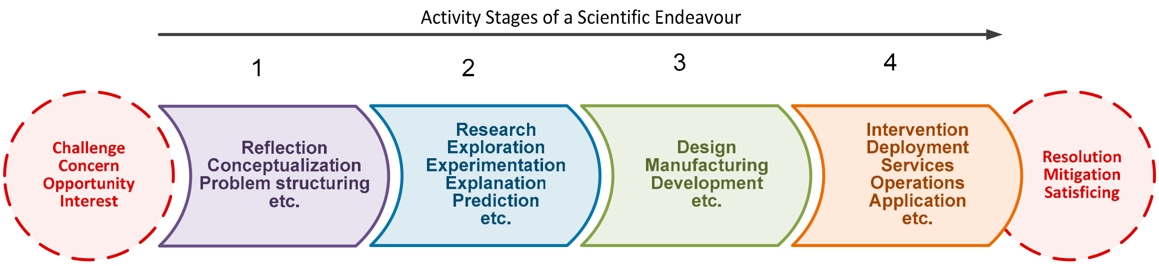

Figure 4. The basic activity stages of a scientific endeavour.

In order to simplify the discussion I will subsume the various terms used in each stage under ones I will take to stand for the "essence" of each stage, proposing that the essence of stage 1 is "reflection", stage 2 is "research", stage 3 is "design", and stage 4 is "intervention". Each of these stages of activity leads to outputs specific to that type of activity as shown in Figure 5.

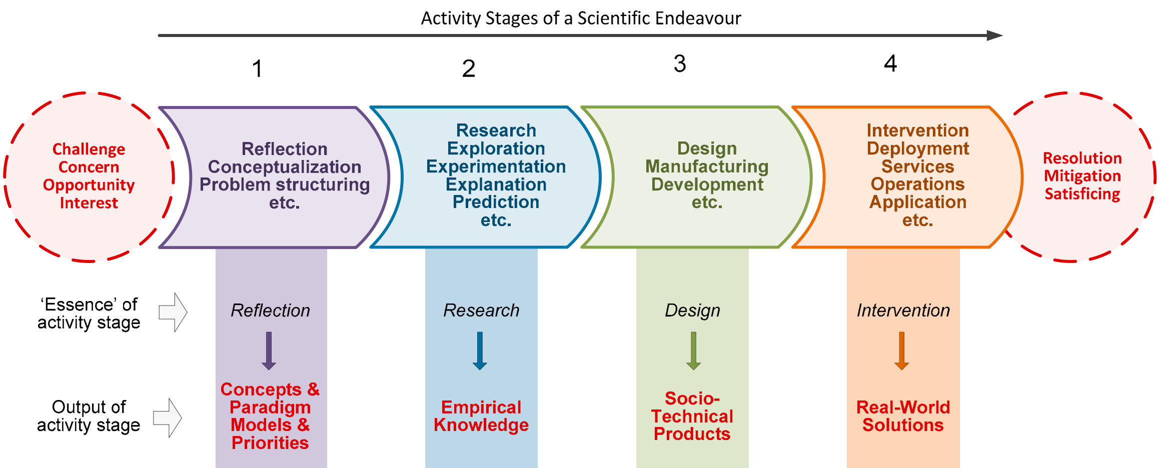

Figure 5. The typical outputs of stages of a scientific endeavour.

The type of activity in each stage is supported by methods and principles that are similar whatever the discipline under which the project is being done. The cross-disciplinary similarity of the principles, methods and outputs of each type of stage has resulted in disciplinary specializations that each have of one of the "essences" as their central concern, and we can group such disciplines together under the "disciplinary fields" of philosophy, science, engineering, and practice. These fields each lead the way in developing the principles and methods of their essential focus, but it should be remembered that every scientific discipline engages all the stages of activity. For example, the discipline of medicine has a practice element (e.g., via doctors working in hospitals), an engineering element (e.g., doctors working on medical device development in industry), a science element (e.g., doctors researching disease aetiology in laboratories), and a philosophy element (e.g., doctors developing or enforcing standards in medical ethics), so a disciplinarian can specialise in any of the field dimensions. However, in general every disciplinarian engages with all of the dimensions on every project, as illustrated in Figure 2, so, e.g., an engineering project will typically involve reflection, research, product development and product deployment. These "field dimensions" represent different kinds of hats the same person can wear on the same project without leaving their discipline. That said, the activity level of each discipline is different in the different field dimensions, tapering off away from the essential focus, as illustrated in Figure 6.

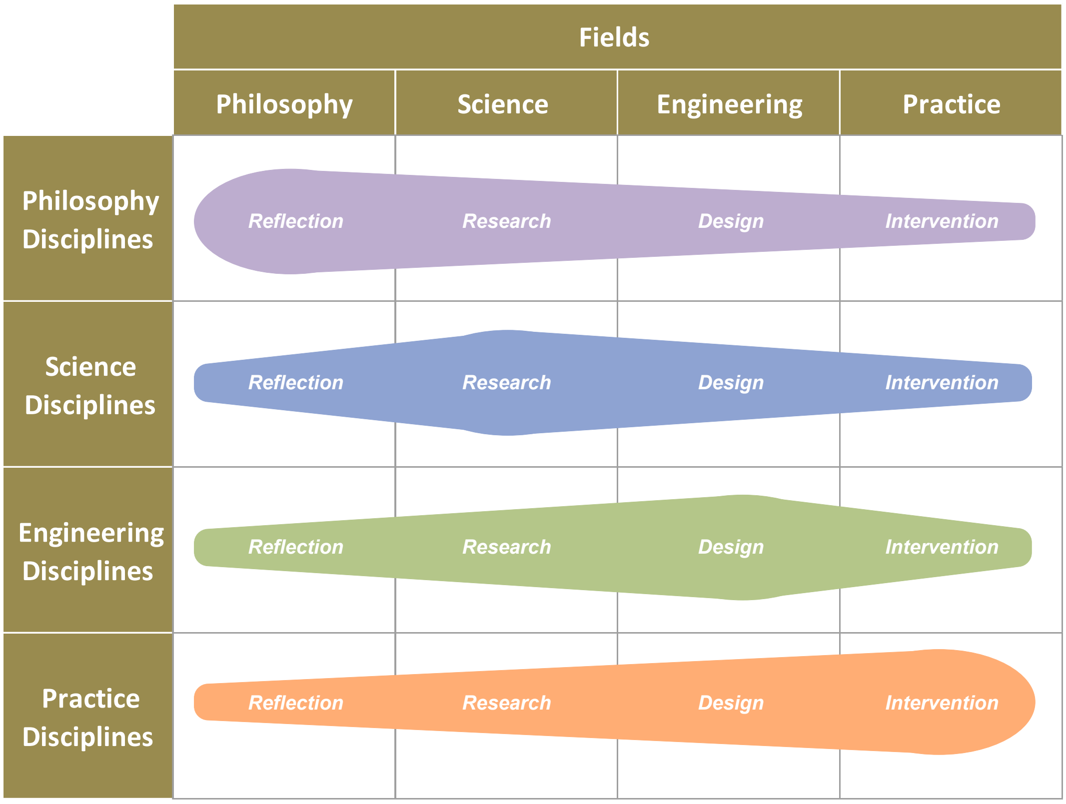

Figure 6. A scientific discipline's typical activity level per field dimension.

If we keep in mind the important observation that all disciplines cut across all the field dimensions, we can shift our analysis to looking at the fields, and so analyse the nature and evolution of the principles underlying each field of activity. This shift is helpful because we can learn from the aggregate progress in a field dimension, and the fields have overall roles from which we can learn lessons valuable for the evolution of the specialized disciplines, as will be shown below.

Figure 7 identifies the empirical disciplinary fields, and shows that they have similar structures for producing their typical outputs (in each case, methods that support activity that produce an output), but for each field the output is something different, analogous to the outputs shown in Figure 5.

In addition, we can generalize over the outputs to associate the fields with distinct roles, as also shown in the lower section of Figure 7. These roles are systemically connected, as indicated[7].

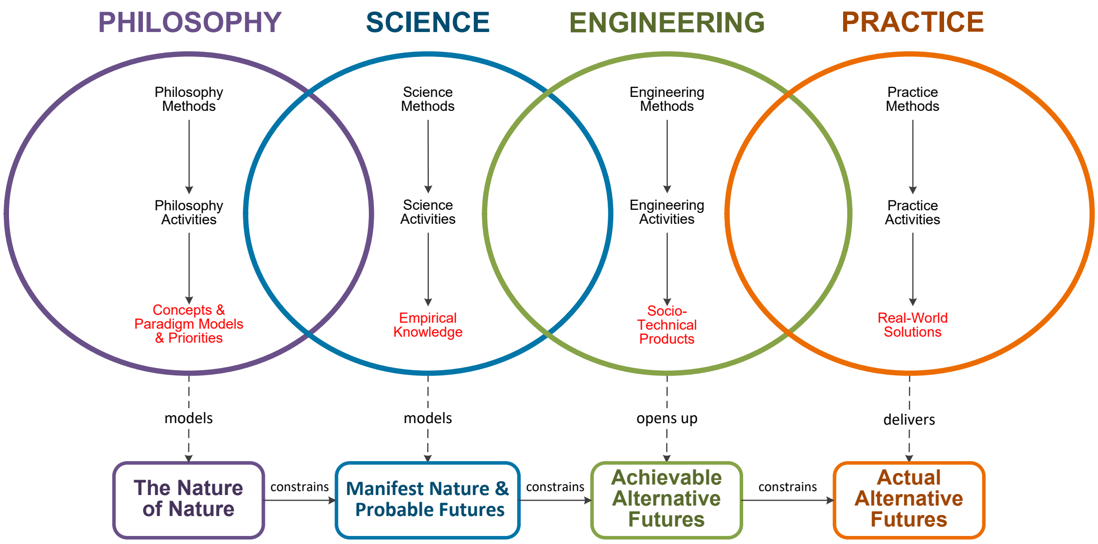

Figure 7. The basic structure and roles of disciplinary fields.

In practice, the fields are connected via common grounds, and this is indicated by the overlaps shown in Figure 7. On inspection it becomes clear that this connection happens via shared principles, as follows. The methods that underpin each field's activities operationalize principles, which (by definition) are guidelines for making judgements and taking action. Given how the phases of a scientific endeavour follow on each other, it is clear that each phase rests on the achievements of the preceding one. The natural way for this to work is for the detailed findings of one phase to be distilled into principles that can be used to develop methods for the next phase. For example, from the explanatory theories of the sciences we can distil "explanatory principles" that can not only be used to help explain further empirical phenomena, but also be interpreted as "design principles" that engineers can use for creating systems that will exhibit similar behaviours or qualities. In this way the same principles can be referred to using different vocabularies but really represent the same thing.

We can illustrate this progression in the distillation and operationalization of shared principles as shown in Figure 8. The indicated ways in which principles are referred to by differently specialised disciplinarians are indicative only, and not intended to be exhaustive.

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[7] For brevity I will gloss over the distinction between methods and methodologies, and for simplicity I will for now ignore the conceptual fields such as Mathematics and Logic. Moreover I will take the sciences to embrace the social and human sciences in addition to the so-called "hard" sciences. For pragmatic reasons I will treat Practice as if it is an integrated field, but of course in reality it is usually presented in academia as disciplinary extensions of specialized disciplines. Nevertheless the practices do fall under common regulatory frameworks, and have similar roles. Likewise for brevity I will here use the term "Philosophy" to refer only to branches of philosophy that adopt the scientific attitude as discussed earlier.

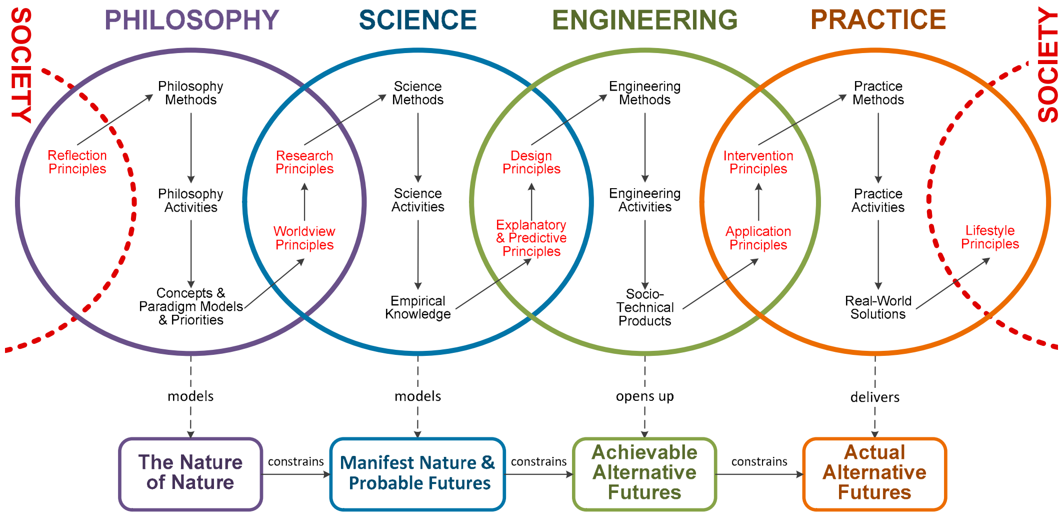

Figure 8. The scientific development of principles across disciplinary fields.

Of course philosophy methods also depend on principles, and the existence of real-world solutions can be translated into principles too, as also shown in Figure 8. These principles connect the disciplinary endeavours with society, in which reflective agents uncover the concerns that motivate the whole spectrum of scientific endeavours, and in which the delivered solutions resolve, ameliorate, or satisfice the concerns. This connection is suggested via the dashed circle segment at each end of the sequence, echoing the symbolism used in Figure 4.

Apart from the flow indicated by the solid arrows, it is important to realize that each field inherits not only the principles resulting from the previous one but also the principles and methods that produced that field's output, so we get a cumulative build-up of principles and methods from left to right. This development represents an 'inheritance' pathway, where everything becomes increasingly scientific.

Of course there is also a developmental pathway that flows from right to left. This is the "diffusion" pathway, where everything is driven by prior heuristics. In this case, heuristic methods are derived by analysing and standardising pre-established practices derived from trial-and-error activities. Heuristic principles are distilled from those methods, and the heuristics, in turn, can inspire extensions to the methods in the previous field. In this way "folk wisdom" and practical experience can spread from one field to another in the right-to-left direction.

It is important to recognize that this heuristic pathway is the historically dominant route, where people try things out first, and only afterwards try to work out better ways to do things in order to improve consistency or effectiveness or prevent common failures or negative unintended consequences. Of course in practice the "scientific" and "heuristic" pathways operate interactively, creating feedback loops as shown in Figure 9. For example, a heuristic design principle used in engineering could inspire scientific investigations leading to new explanatory theories, yielding new explanatory principles that can "upgrade" the previously heuristic design principle to a more scientific one (e.g., make it more exact, or explain what limits its viable application range).

To illustrate how the causal flows in the diagram follow a loop via the connection with society we can redraw the diagram as shown in Figure 10, with "Society" included as a field of human endeavour that connects and motivates the fields of scientific endeavour. The subjects matters of the disciplines only arise because of our capacities as sentient members of a society, and disciplinary activities only have value insofar as they contribute to addressing issues relevant to members of our society.

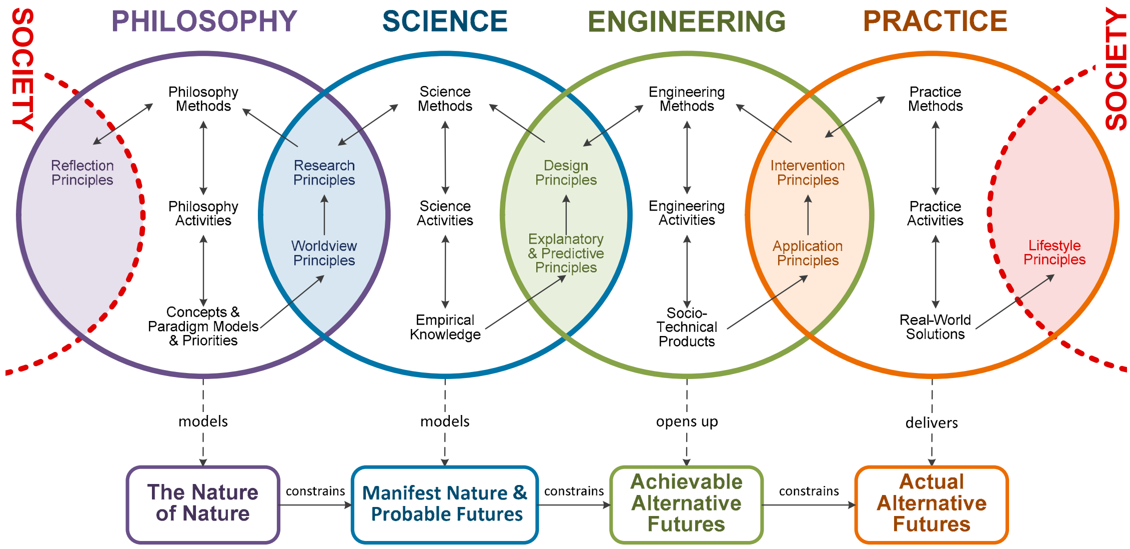

Figure 9. The interplay of scientific and heuristic principles across the field dimensions.

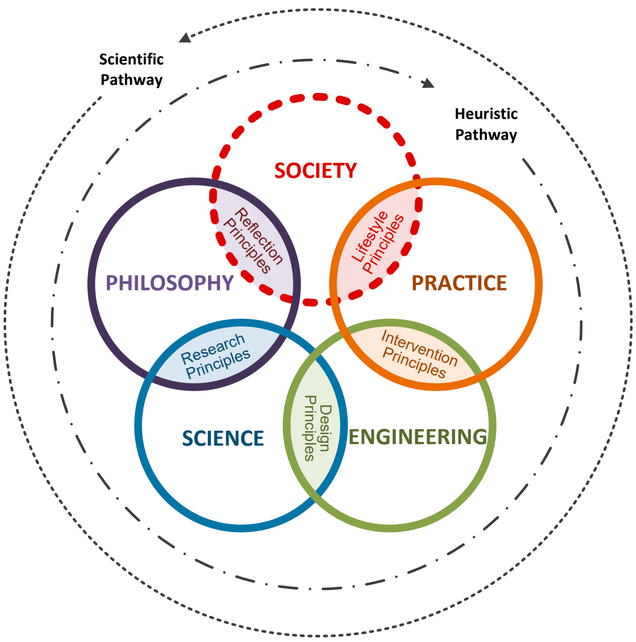

Figure 10. Interplay of pathways driving the emergence and evolution of principles across fields.

The "uncoiled" version of the diagram is easier to work with, so that is how I will continue to present it, but it should be kept in mind that the ends should be taken as connected.

The diagram in Figure 11 provides a general architecture for the relationships between the disciplinary fields, and this in turn provides a basic structure for developing a typology of the principles that they depend on or produce. I will return to this further below. For now I want to show how this general architecture of a disciplinary field can be used to frame an architecture for systemology and its high-level typology.

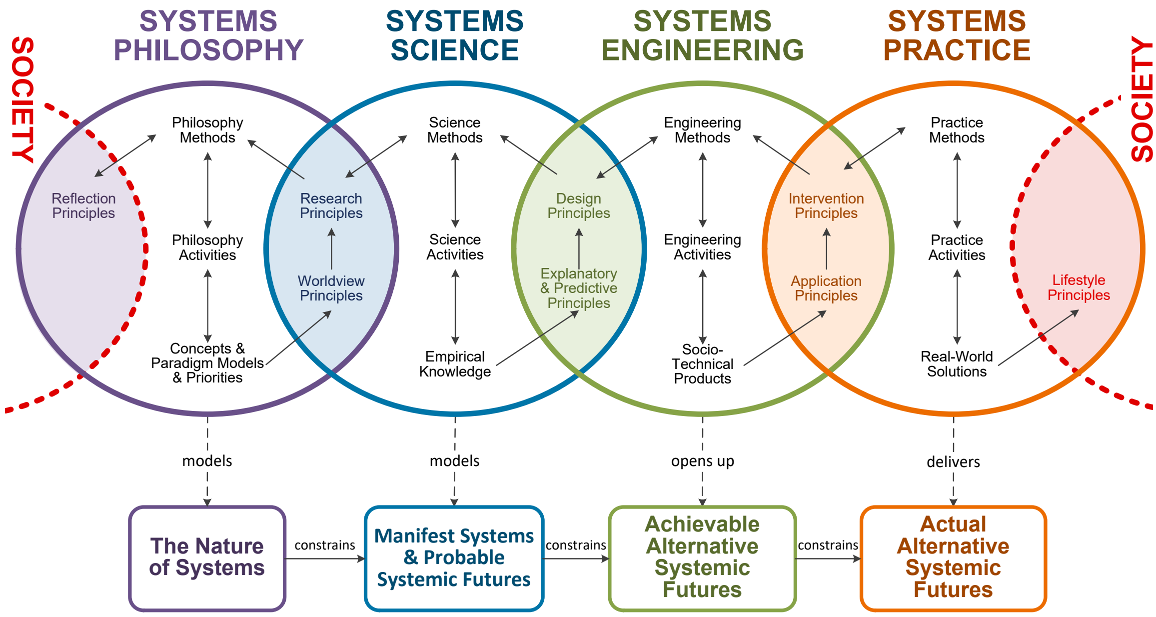

Figure 11. The architecture of systemology.

7. Connection to the Systems Perspective

Each of the mentioned disciplinary fields has a systems specialization, in which disciplinarians engage with the systemic aspects of their subject matter. This is demarcated in Figure 11 as systems philosophy, systems science, systems engineering and systems practice.

I did not add "system" adjectives inside the field-circles, in order to keep the diagram visually simpler, but such adjectives should be taken as entailed by the title over each circle, so 'inside' each we have, e.g., systems research principles, systems engineering activities, systemic real-world solutions, and so on.

Taken together, the set of these systems fields form the transdiscipline called "systemology". The systems fields are connected via the systems principles, the types of which can be separated by reference to the areas of overlap as shown. These have been color-coded in Figures 9–11 to provide a visual cue for the typology structure to be presented next.

8. Types and Sub-Types of Principles

The types of principles indicated by the overlaps shown in Figure 11 can be subdivided according to the nature of the concerns that each field dimension would attempt to address. This can be expressed in terms of a systematic breakdown of their areas of interest. For example, scientific research progressively investigates questions about:

i what things are like (how they look/behave, what they do);
ii how things work;
iii why they work as they do;
iv how they develop (come about as instances); and
v how they arise in evolutionary history (come about as kinds).

The research findings produced can be distilled into "explanatory principles" respectively characterisable as:

i classification principles;
ii design principles;
iii optimality principles;

iv developmental principles; and
v emergence/evolutionary principles.

Engineers can use these principles to develop methods for engineering design, and they would respectively interpret them as:

i design conceptualization principles;
ii functional design principles;
iii design optimization principles;
iv manufacturing/production principles; and
v innovation principles.

All of the main types of principles can be analysed in this way to identify subtypes. The diagram in Figure 12 provides a schema that does this in a provisional way for each of the scientific endeavour stages, indicating the kinds of questions addressed in each stage and the kinds of principles that are used in or result from pursuing them. Examples of systems principles are suggested in each case. This example has not been refined or optimised, but is only given to demonstrate the potential of this approach. In order to correlate the structure of the typology with the architecture given above the main types of the principles have been coloured correspondingly.

The table reflects that there are four main types of principles, respectively giving guidance for reflection, research, design, and intervention. Each type can be further subdivided into subtypes, as illustrated, as reflecting principles for guidance regarding key questions to be asked in each kind of activity. The sequence of these questions reflects what is effective for that kind of activity, and so may be peculiar to each case. For example, the sequence of the research questions listed above is defended in [57].

For brevity and simplicity no *general* structure is given in Figure 12 for subdividing the principles, the focus being rather on a natural sequence of questions for each type of activity. However, a general structure can be suggested, although developing it in detail is beyond the scope of the present paper. A short discussion of this can be given here, but for more detail please consult [58,59].

Stage	Key Questions	Subtypes of Principles	Examples of Systems Principles
Reflection	What is the issue?	Focus Principles	estabish clear boundaries
	What is the context?	Perspective Principles	systems are conditioned by systemic relationships
	What might happen?	Exploration Principles	systems change in a network balancing way
	Why does this matter?	Evaluation Principles	systemic changes have causes and consequences
	What are the risks/uncertainties?	Confidence Principles	we can only influence the systems we recognize
	What can/should we do?	Actioning Principles	dance with the systems; respect the stakeholders
Research	What is it? What is it like?	Classification Ps	systems, boundaries, relationships
	Where does it occur?	Ecological Ps	almost everything is part of a greater system
	How does it work?	Functionality Ps	emergent properties entail submergence
	Why does it work this way?	Optimization Ps	explore emergence/submergence interplay
	How did it get like this?	Developmental Ps	systems emerge from stable relationships
	How did it arise?	Evolutionary Ps	balance technical and social needs
Design	What should it be like?	Conceptualization Ps	hierarchical organization provides robustness
	How could it work?	Functional Design Ps	stability via setpoint and negative feedback
	Why should it work this way?	Design Optimization Ps	minimise resource use, maximize effectiveness
	How can we provide it?	Manufacturing Ps	integrate simpler systems to make complex ones
	Is there a better way to do this?	Innovation Ps	open systems create integration opportunities
	How can we sustain it?	Maintenance Ps	maintenance and repair depend on systems too
Intervention	Can we preserve it?	Prevention Ps	protect the hyper-nodes
	Can we change it back/recover it?	Restoration Ps	restore its structure and relationships
	Can we make it grow/multiply?	Expansion Ps	protect the systems it depends on
	Can we change it?	Transformation Ps	adjust the internal and/or external relationships
	Can we get hold of it?	Establishment PS	leverage relationship: supply - demand systems
	Can we get rid of it?	Dismantling Ps	cut at the joints in the hierarchical structure

note: for simplicity I here show input principles for reflection, output principles for research, input principles for design and input principles for intervention

Figure 12. A typology for systems principles.

Briefly, a general substructure is suggested by reflection on the variety of questions that could be posed in each field or activity stage. This variety corresponds to the kinds of knowledge one could wish to have about that (or indeed any) issue. The general case of this is represented by the general structure of a worldview, which is discussed in [6,60]. If we employ this structure we can view any particular problem as a special case of the general problem of knowing what there is, learning about it, identifying relevant values, and motivating various actions. In this way the structure of a worldview can provide us with a "checklist" if the kinds of questions we could ask in relation to any problem at every project stage. A brief example of the structure of a worldview and the questions in play relative to each worldview component is given in Table 1. Additionally, as shown in Table 1, is a matching set of research questions suggested by the worldview questions. The same can be done for the other fields/stages, as discussed elsewhere [58,59].

Table 1. The components of a worldview mapped to research questions.

Worldview Components	Worldview Questions	Research Questions
Ontology	What exists?	What is it? What is it like?
Metaphysics	What is its nature?	What does it do? How does it work? What sustains/degrades it?
Epistemology	What/How can we know?	What can we (not) know about it?
Cosmology	What is its origin/history/current state/destiny?	How did it get here? How did it get like this? What might happen to it?
Axiology	What is important and why?	Why does it work this way?
Praxeology	How should we live and why?	How should we (not) study it?

The worldview perspective gives an additional dimension for classifying principles, one that is applicable across all fields and project stages. In this way the principles in any field can be classified in terms of being ontological, metaphysical, epistemological, cosmological, axiological, or praxeological. This is, of course, an independent consideration from the distinctions identified previously. Overall this suggests that to classify systems principles at least four typological dimensions need to be considered, namely whether the principles are:

i Reflection, research, design, or intervention principles. This is the major division, but afterwards they can be subdivided as needed into:
ii General or specialized principles;
iii Heuristic or scientific principles; and
iv Ontological, metaphysical, epistemological, cosmological, axiological, or praxeological principles.

With these distinctions in hand it is now possible to establish a systematic catalogue and status assessment of systems principles and, hence, to prioritise research towards making them more comprehensive and more scientific.

9. Conclusions

One way of addressing the challenge of complexity in systems engineering is to develop more scientific principles for basing its methods on. In this paper, it is argued that improvement in systems engineering's methods depends on making the principles of systemology, of which systems engineering is a part, more diverse and more scientific. An architecture for systemology is introduced, and this shows how the principles of systemology arise from interdependent processes spanning multiple fields. On this basis a typology is introduced, which can be used to classify systems principles (and consequently the methods that operationalize them). This framework, consisting of an architecture and a typology, can be used to survey and classify the principles and methods currently in use, map vocabularies referring to them, identify key gaps, and expose opportunities for further development.

It may, thus, serve as a tool for coordinating collaborative work towards advancing the scope and depth of systemology.

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References

1. Ackoff, R.L. Science in the Systems Age: Beyond IE, OR, and MS. *Oper. Res.* **1971**, *21*, 661–671. [CrossRef]
2. Pouvreau, D.; Drack, M. On the history of Ludwig von Bertalanffy's "General Systemology". And on its relationship to cybernetics, Part 1. *Int. J. Gen. Syst.* **2007**, *36*, 281–337. [CrossRef]
3. Von Bertalanffy, L. An Outline of General System Theory. *Br. J. Philos. Sci.* **1950**, *1*, 134–165. [CrossRef]
4. Von Bertalanffy, L. *General System Theory: Foundations, Development, Applications, Revised Edition*; Braziller: New York, NY, USA, 1976.
5. Mekios, C. Organizing principles as tools for bridging the gap between system theory and biological experimentation. *History Philos. Life Sci.* **2016**, *38*, 1–25. [CrossRef] [PubMed]
6. Rousseau, D.; Wilby, J.M.; Billingham, J.; Blachfellner, S. A Typology for the Systems Field. *Systema* **2016**, *4*, 15–47.
7. McNeil, D.H. A survey of applied systemology. *Syst. Res.* **1995**, *12*, 133–145. [CrossRef]
8. Fuenmayor, R.; López-Garay, H. The scene for interpretive systemology. *Syst. Pract.* **1991**, *4*, 401–418. [CrossRef]
9. Lineberger, R. Deloitte Study: Cost Overruns Persist in Major Defense Programs—Press Release | Deloitte US, Deloitte United States, 24 October 2016. 2017. Available online: https://www2.deloitte.com/us/en/pages/about-deloitte/articles/press-releases/cost-overruns-persist-in-major-defense-programs.html (accessed on 27 February 2017).
10. Flyvbjerg, B. What you should know about megaprojects and why: An overview. *Proj. Manag. J.* **2014**, *45*, 6–19. [CrossRef]
11. Jones, D. 66% of IT Projects Fail. *Proj. J. Proj. Manag.* **2016**. Available online: https://projectjournal.co.uk/2016/02/20/66-of-it-projects-fail/ (accessed on 20 February 2016).
12. Award#1645065—EAGER/Collaborative Research: Lectures for Foundations in Systems Engineering. Available online: https://www.nsf.gov/awardsearch/showAward?AWD_ID=1645065&HistoricalAwards=false (accessed on 15 January 2017).
13. Krigsman, M. Worldwide Cost of IT Failure (Revisited): $3 Trillion. ZDNet, 10 April 2012. 2017. Available online: http://www.zdnet.com/article/worldwide-cost-of-it-failure-revisited-3-trillion/ (accessed on 27 November 2017).
14. Hardy-Vallee, B. *The Cost of Bad Project Management*; Business Journal; Gallup Inc.: Washington, DC, USA, 2012.
15. Syal, R. Abandoned NHS IT System Has Cost £10bn So Far. Available online: https://www.theguardian.com/society/2013/sep/18/nhs-records-system-10bn (accessed on 13 March 2018).
16. Collopy, P.D.; Mesmer, B.L. Report on the Science of Systems Engineering Workshop. In Proceedings of the 53rd AIAA Aerospace Sciences Meeting, Kissimmee, FL, USA, 5–9 January 2015; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2015; pp. 1–4.
17. International Council on Systems Engineering (INCOSE). *A World in Motion—Systems Engineering Vision 2025*; INCOSE: San Diego, CA, USA, 2014.
18. Rousseau, D.; Wilby, J.M.; Billingham, J.; Blachfellner, S. Manifesto for General Systems Transdisciplinarity (GSTD). Presented at the 59th Conference of the International Society for the Systems Sciences (ISSS), Berlin, Germany, 4 August 2015.
19. Wilby, J.M.; Rousseau, D.; Midgley, G.; Drack, M.; Billingham, J.; Zimmermann, R. Philosophical Foundations for the Modern Systems Movement. In *Systems Thinking: New Directions in Theory, Practice and Application, Proceedings of the 17th Conversation of the International Federation for Systems Research, St. Magdalena, Linz, Austria, 27 April–2 May 2014*; SEA-Publications: Linz, Austria, 2015; pp. 32–42.

20. Von Bertalanffy, L. *General System Theory, General Systems*; Article Reprinted in *Systems Thinking*; Midgley, G., Ed.; Sage: London, UK, 2003; Volume 1, pp. 36–51.
21. Hitchins, D.K. *Putting Systems to Work*; John Wiley & Sons: Chichester, UK, 2014.
22. Mobus, G.E.; Kalton, M.C. *Principles of Systems Science*, 2015 ed.; Springer: New York, NY, USA, 2014.
23. Walden, D.D.; Roedler, G.J.; Forsberg, K.J.; Hamelin, R.D.; Shortell, T.M. (Eds.) *Systems Engineering Handbook*, 4th ed.; Wiley: Hoboken, NJ, USA, 2015.
24. Augustine, N.R. *Augustine's Laws*; Penguin: New York, NY, USA, 1987.
25. Gall, J. *Systemantics: How Systems Work and Especially How They Fail*; Pocket Books: New York, NY, USA, 1978.
26. Senge, P.M. *The Fifth Discipline: The Art and Practice of the Learning Organization*; Random House: London, UK, 1990.
27. Maier, M.W.; Rechtin, E. *The Art of Systems Architecting*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2009.
28. Whitney, K.; Bradley, J.M.; Baugh, D.E.; Chesterman, C.W., Jr. Systems theory as a foundation for governance of complex systems. *Int. J. Syst. Syst. Eng.* **2015**, *6*, 15–32. [CrossRef]
29. Katina, P.F. Systems Theory as a Foundation for Discovery of Pathologies for Complex System Problem Formulation. In *Applications of Systems Thinking and Soft Operations Research in Managing Complexity*; Springer: Cham, Switzerland, 2016; pp. 227–267.
30. Adams, K.M.; Hester, P.T.; Bradley, J.M.; Meyers, T.J.; Keating, C.B. Systems Theory as the Foundation for Understanding Systems. *Syst. Eng.* **2014**, *17*, 112–123. [CrossRef]
31. Von Bertalanffy, L. *General System Theory: Foundations, Development, Applications*; Braziller: New York, NY, USA, 1969.
32. Francois, C. (Ed.) *International Encyclopedia of Systems and Cybernetics*; Saur Verlag: Munich, Germany, 2004.
33. Danielle-Allegro, B.; Smith, G. *Exploring the Branches of the Systems Tree*; Les Editions Allegro Brigitte D: Castelnau d'Estretefonds, France, 2016.
34. Heylighen, F. Self-Organization of Complex Intelligent Systems: An Action Ontology for Transdisciplinary Integration. Available online: http://pespmc1.vub.ac.be/Papers/ECCO-paradigm.pdf (accessed on 13 March 2018).
35. Kramer, N.J.T.A.; De Smit, J. *Systems Thinking: Concepts and Notions*; Martinus Nijhoff: Leiden, The Netherlands, 1977.
36. Schindel, W.D. *Abbreviated Systematica^{TM} 4.0 Glossary—Ordered by Concept*; ICTT System Sciences: Terre Haute, IN, USA, 2013.
37. Schoderbek, P.P.; Schoderbek, C.G.; Kefalas, A.G. *Management Systems: Conceptual Considerations (Revised Edition)*; IRWIN: Boston MA, USA, 1990.
38. Wimsatt, W. *Re-Engineering Philosophy for Limited Beings: Piecewise Approximations to Reality*; Harvard University Press: Cambridge, MA, USA, 2007.
39. Sillitto, H.; Dori, D.; Griego, R.M.; Jackson, S.; Krob, D.; Godfrey, P. Defining "System": A Comprehensive Approach. In Proceedings of the 27th Annual INCOSE International Symposium (IS), Adelaide, Australia, 15–20 July 2017; Volume 27, pp. 170–186.
40. Rousseau, D. Three General Systems Principles and their Derivation: Insights from the Philosophy of Science Applied to Systems Concepts. In Proceedings of the 15th Annual Conference on Systems Engineering Research—Disciplinary Convergence: Implications for Systems Engineering Research, Los Angeles, CA, USA, 23–25 March 2017.
41. Calvo-Amodio, J.; Kittelman, S.; Wang, S. Applications of Systems Science Principles. Presented at the Workshop on "Systems Science—Principles for the Evolution of Systems", International Annual Conference of the American Society for Engineering Management (ASEM) on the theme "Reimagining Systems Engineering and Management", Huntsville, AL, USA, 18–21 October 2017.
42. Rueger, A.; McGivern, P. Hierarchies and levels of reality. *Synthese* **2010**, *176*, 379–397. [CrossRef]
43. Poli, R. The Basic Problem of the Theory of Levels of Reality. *Axiomathes* **2001**, *12*, 261–283. [CrossRef]
44. Boulding, K.E. General systems theory—The skeleton of science. *Manag. Sci.* **1956**, *2*, 197–208. [CrossRef]
45. Rousseau, D. Systems Research and the Quest for Scientific Systems Principles. *Systems* **2017**, *5*, 25. [CrossRef]
46. Bunge, M. *Emergence and Convergence: Qualitative Novelty and the Unity of Knowledge*; University of Toronto Press: Toronto, ON, USA, 2003.
47. Bunge, M. *Ontology II: A World of Systems*; Reidel: Dordrecht, The Netherlands, 1979.

48. Schindel, W.D. What is the Smallest Model of a System? In Proceedings of the INCOSE 2011 International Symposium, International Council on Systems Engineering, Denver, CO, USA, 20–23 June 2011; pp. 99–113.
49. Ackoff, R.L. Towards a System of Systems Concepts. *Manag. Sci.* **1971**, *17*, 661–671. [CrossRef]
50. Sillitto, H.; Dori, D.; Griego, R.; Krob, D.; Arnold, E.; McKinney, D.; Godfrey, P.; Martin, J.; Jackson, S. What do we mean by "system"?—System Beliefs and Worldviews in the INCOSE Community. In Proceedings of the INCOSE International Symposium, Washington, DC, USA, 7–12 July 2018. Under review.
51. Friendshuh, L.; Troncale, L.R. Identifying Fundamental Systems Processes for a General Theory of Systems. In Proceedings of the 56th Annual Conference, International Society for the Systems Sciences (ISSS), San Jose State University, San Jose, CA, USA, 15–20 July 2012; p. 23.
52. Troncale, L.R. Linkage Propositions between fifty principal systems concepts. In *Applied General Systems Research*; Klir, G.J., Ed.; Plenum Press: New York, NY, USA, 1978; pp. 29–52.
53. McNamara, C.; Troncale, L.R. SPT II.: How to Find & Map Linkage Propositions for a General Theory of Systems from the Natural Sciences Literature. In Proceedings of the 56th Annual Conference, International Society for the Systems Sciences (ISSS), San Jose State University, San Jose, CA, USA, 15–20 July 2012; p. 17.
54. Rousseau, D. Strategies for Discovering Scientific Systems Principles. *Syst. Res. Behav. Sci.* **2017**, *34*, 527–536. [CrossRef]
55. Troncale, L.R. The future of general systems research: Obstacles. Potentials, case studies. *Syst. Res.* **1985**, *2*, 43–84. [CrossRef]
56. Troncale, L.R. The systems sciences: What are they? Are they one, or many? *Eur. J. Oper. Res.* **1988**, *37*, 8–33. [CrossRef]
57. Rousseau, D.; Billingham, J.; Wilby, J.M.; Blachfellner, S. In Search of General Systems Theory. *Systema* **2016**, *4*, 76–92.
58. Rousseau, D. A Systematic Framework for Comparing Worldviews. 2018; in preparation.
59. Rousseau, D. Systems Principles and Worldviews. In Proceedings of the Workshop Presented in the Systems Science Working Group (SSWG) in the International Workshops (IW18) of the International Council on Systems Engineering, Jacksonville, FL, USA, 20–23 January 2018.
60. Rousseau, D.; Billingham, J.; Wilby, J.M.; Blachfellner, S. The synergy between General Systems Theory and the General Systems Worldview. *Systema* **2016**, *4*, 61–75.