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Systems Theory as the Foundation for Understanding Systems

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ABSTRACT

As currently used, *systems theory* is lacking a universally agreed upon definition. The purpose of this paper is to offer a resolution by articulating a formal definition of systems theory. This definition is presented as a unified group of specific propositions which are brought together by way of an axiom set to form a system construct: systems theory. This construct affords systems practitioners and theoreticians with a prescriptive set of axioms by which a system must operate; conversely, any set of entities identified as a system may be characterized by this set of axioms. Given its multidisciplinary theoretical foundation and discipline-agnostic framework, systems theory, as it is presented here, is posited as a general approach to understanding system behavior. © 2013 Wiley Periodicals, Inc. Syst Eng 17: 112–123, 2014

Key words: systems theory; axiom set; systems propositions

1. INTRODUCTION

Systems theory is a term frequently mentioned in the systems literature. As currently used, *s*ystems theory is lacking a universally agreed upon definition. Examples of multiple definitions are provided in Table I. Two of the definitions in Table I refer to General Systems Theory, a concept espoused by Ludwig von Bertalanffy, Kenneth Boulding, Anatol Rapoport, and Ralph Gerard in the original 1954 bylaws for the foundation of the Society for General Systems Research (SGSR). The aims of General Systems Theory (GST), as stated in the SGSR bylaws, were [Hammond, 2002: 435–436]:

1. To investigate the isomorphy of concepts, laws, and models from various fields, and to help in useful transfers from one field to another
2. To encourage development of adequate theoretical models in fields which lack them
3. To minimize the duplication of theoretical effort in different fields
4. To promote the unity of science through improving communications among specialists.

Peter Checkland [1993: 93] remarked that "the general theory envisaged by the founders has certainly not emerged, and GST itself has recently been subject to sharp attacks by both Berlinski (1976) and Lilienfield (1978)."

We believe that this is because GST [Bertalanffy, 1968] did not provide either a construct for systems theory or the supporting axioms and propositions required to fully articulate and operationalize a theory.

In order to improve the depth of understanding for systems practitioners using the term *systems theory*, we believe that a more unifying definition and supporting construct need to be

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Table I. Definitions for Systems Theory

Definition	Author and Year
The formal correspondence of general principles, irrespective of the kinds of relations or forces between the components, lead to the conception of a 'General Systems Theory' as a new scientific doctrine, concerned with the principles which apply to systems in general.	Bertalanffy (1950b)
General systems theory is the skeleton of science in the sense that it aims to provide a framework or structure of systems on which to hang flesh and blood of particular disciplines and particular subject matters in an orderly and coherent corpus of knowledge.	Boulding (1956)
A new way of looking at the world in which individual phenomena are viewed as interrelated rather than isolated, and complexity has become a subject of interest.	Klir (1972)
General Systems Theory and the Systems Approach grapple with the issue of 'simplicity' and 'complexity' by which the relationships among systems and subsystems are decided. The problems of 'optimization' and 'suboptimization' are central to explaining the fruitless efforts of systems designers who reach for the 'summum bonum' while settling for a 'second best.'	van Gigch (1974)

articulated. Although there is not a generally accepted canon of general theory that applies to systems, we believe that there are a number of individual systems propositions that are relevant to a common practical perspective for systems theory. We therefore propose a formal definition and supporting construct for systems theory.

We propose that systems theory is a unified group of specific propositions which are brought together to aid in understanding systems, thereby invoking improved explanatory power and interpretation with major implications for systems practitioners. It is precisely this group of propositions that enables thinking and action with respect to systems. However, there is no one specialized field of endeavor titled *systems* from which systems theory may be derived. Rather, the propositions available for inclusion into a theory of systems come from a variety of disciplines, thereby making its underlying theoretical basis inherently multidisciplinary. This paper will (1) discuss the functional fields of science in which systems theory can be grounded, (2) provide a definition, construct, and proposed taxonomy of axioms (an axiom set) for systems theory and its associated supporting propositions, derived from the fields of science, and (3) conclude by providing an introductory view of the multidisciplinary breadth represented by systems theory.

2. INDIVIDUAL FIELDS OF SCIENCE

We propose that science has a hierarchical structure for knowledge contributions as shown in Table II. The Organization for Economic Co-operation and Development (OECD) has provided an internationally accepted classification for the fields of science [OECD, 2007]. This classification includes six major sectors and 42 individual fields of science. The major sectors and individual fields of science are described in Table III. The 42 individual fields of science in Table III serve

Table II. Structure for Knowledge Contributions

Level	Basic Description
Philosophical	The emerging system of beliefs providing grounding for theoretical development
Theoretical	Research focused on explaining phenomena related to scientific underpinnings and development of explanatory models and testable conceptual frameworks
Methodological and axiomatic	Investigation into the emerging propositions, concepts, and laws that define the field and provide high level guidance for design and analysis
Technique	Specific models, technologies, standards, and tools for implementation

Table III. Major and Individual Fields of Science [OECD, 2007]

Major Fields of Science	Natural Science	Engineering and Technology	Medical and Health Sciences	Agricultural Sciences	Social Sciences	Humanities
Individual Fields of Science	1. Mathematics	8. Civil engineering	19. Basic medicine	24. Agriculture, forestry, and fisheries	29. Psychology	38. History and archaeology
	2. Computer and information sciences	9. Electrical engineering, electronic engineering, information engineering	20. Clinical medicine	25. Animal and dairy science	30. Economics and business	39. Languages and literature
	3. Physical sciences	10. Mechanical engineering	21. Health sciences	26. Veterinary science	31. Educational sciences	40. Philosophy, ethics and religion
	4. Chemical sciences	11. Chemical engineering	22. Health biotechnology	27. Agricultural biotechnology	32. Sociology	41. Art (arts, history of arts, performing arts, music)
	5. Earth and related environmental sciences	12. Materials engineering	23. Other medical sciences	28. Other agricultural sciences	33. Law	42. Other humanities
	6. Biological sciences	13. Medical engineering			34. Political Science	
	7. Other natural sciences	14. Environmental engineering			35. Social and economic geography	
		15. Environmental biotechnology			36. Media and Communications	
		16. Industrial Biotechnology			37. Other Social Sciences	
		17. Nano-technology				
		18. Other engineering and technologies				

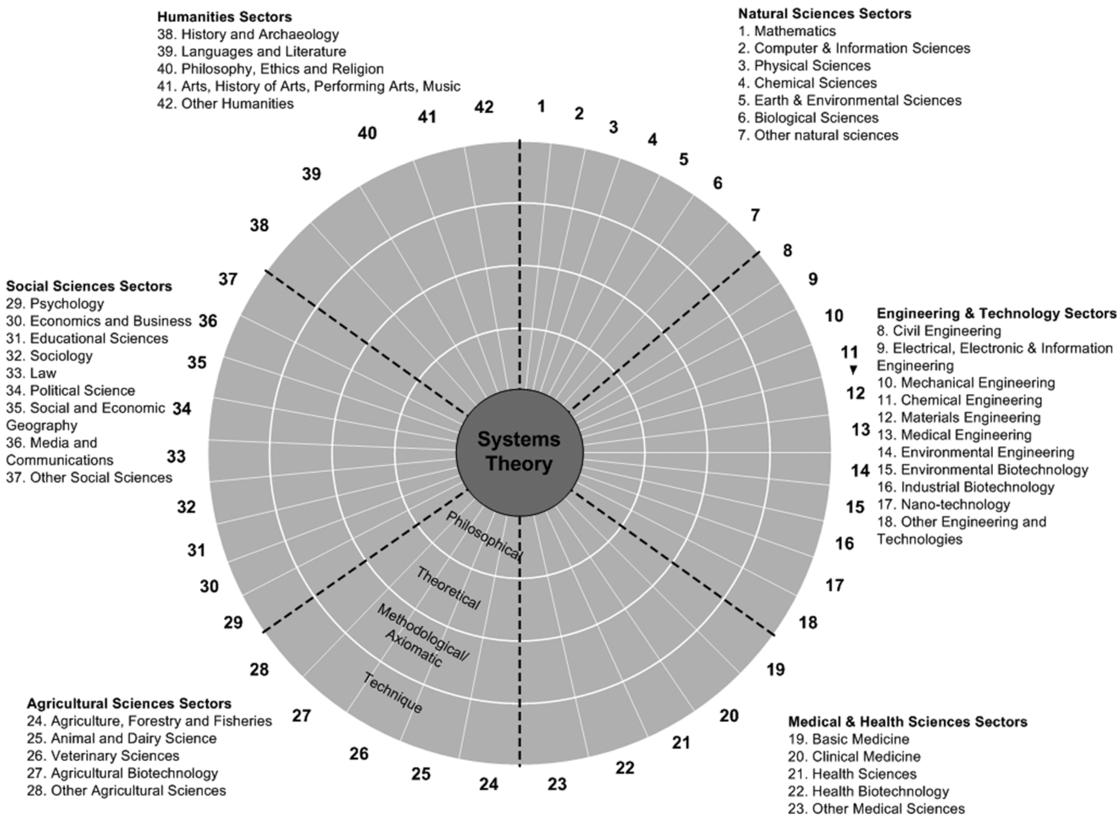

Figure 1. Depiction of knowledge and the fields of science.

as the source for the propositions that are brought together to form a construct for systems theory.

These structural elements constitute the major contributions on which each scientific field's body of knowledge is founded. We display this concept by using a series of concentric rings where the level of knowledge contribution (Table II) radiates from the center and each of the 42 specific fields of science (Table III) is a sector on the circle. Figure 1 is a simplified diagram of how we can account for the knowledge from within a functional field of science.

3. SYSTEMS THEORY

We believe that the underlying theoretical basis developed in this paper will provide an appropriate foundation for understanding systems. Understanding the axioms and propositions that underlie all systems is mandatory for developing a universally accepted construct for systems theory. The sections that follow will describe our notion of theory, propose a group of constituent propositions, construct a set of proposed axioms, and provide a construct for systems theory.

3.1. Introduction to Theory

Theory is defined in a variety of ways. Table IV is a collection of definitions for theory and the key elements associated with each. From these definitions it should be clear that a theory does not have a single proposition that defines it, but is a population of propositions (i.e., arguments, hypotheses, predictions, explanations, and inferences) that provide a skeletal structure for explanation of real-world phenomena. Drawing on the literature, we define theory as follows:

> A unified system of propositions made with the aim of achieving some form of understanding that provides an explanatory power and predictive ability.

The relationship between theory and its propositions is not a direct relationship. It is indirect, through the intermediary of the axioms, where the links in the theory represent the correspondence through similarity to the empirical, real-world system. Figure 2 depicts these relationships.

Our notion of theory is a population of propositions that "... explains a [real system in terms of a] large set of observations or findings. Those constituent findings are the product of scientific research and experimentation, those findings, in other words, already have been verified, often many times over, and are as close to being 'facts' as science cares to characterize them" [Angier, 2007: 154]. Our representation of theory subscribes to the model espoused by Giere [1988: 87] where "rather than regarding the axioms and theorems as empirical claims, treat them all merely as definitions." In this case, our model of systems theory is defined by its set of axioms and supporting propositions.

The following section will use the axiomatic method [Audi, 1999, p. 65] to articulate the accepted propositions and

Table IV. Definitions for Theory

Definition	Key Elements
A scientific theory is an attempt to bind together in a systematic fashion the knowledge that one has of some particular aspect of the world of experience. The aim is to achieve some form of understanding, where this is usually cashed out as an explanatory power and predictive fertility (Honderich, 2005, p. 914).	• Bind together in a systematic fashion • Explanatory power and predictive fertility
A unified system of laws or hypotheses, with explanatory force (Proudfoot & Lacey, 2010).	• Unified system
We understand a theory as comprising two elements: (1) a population of models, and (2) various hypotheses linking those models with systems in the real world (Giere, 1988).	• Population of models • Linked to the real world through hypotheses
An abstract calculus is the logical skeleton of the explanatory system, and implicitly defines the basic notions of the system. A set of rules that assign an empirical content to the abstract calculus by relating it to the concrete materials of observation and experiment. An interpretation or model for the abstract calculus, which supplies some flesh for the skeletal structure in terms of more or less familiar conceptual or visualizable materials (Nagel, 1961).	• Logical skeleton of the explanatory system • Set of rules • Model for the abstract calculus, which supplies some flesh for the skeletal structure
A coherent set of principles or statements that explains a large set of observations or findings (Angier, 2007).	• Set of propositions (Angier's principles) • Explains a large set of observations

concepts from the 42 fields of science discussed in Section 2 of the paper in order to increase certainty in the propositions and clarity in the concepts we propose as *systems theory*.

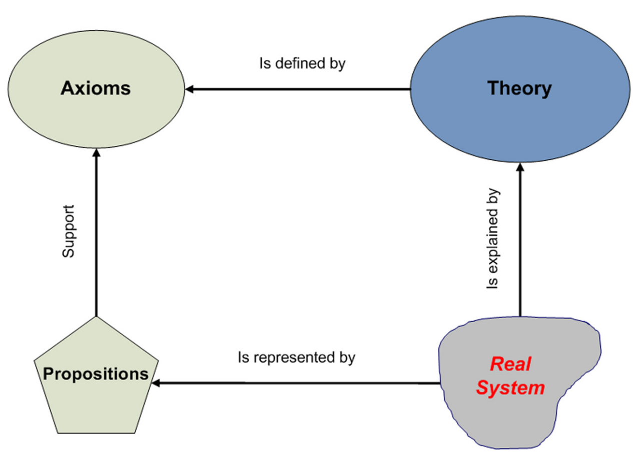

Figure 2. Relationship between theory, propositions, axioms, and real system. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

3.2. Systems Propositions

This section addresses a proposed group of constituent propositions that we have encountered in our work with systems. Each of the propositions has an empirical basis in one of the 42 individual fields of science in Table III. While likely incomplete, this set of propositions provides a representation of real-world systems encountered during our work with systems problems. Each underlying proposition, its primary proponent in the literature, and a brief description are presented in Table V.

3.3. Axioms of Systems Theory

This section addresses a proposed set of axioms and their constituent propositions that we termed *systems theory*. The 30 propositions presented in Section 3.1 supported inductive development of the axioms. Using the axiomatic method [Audi, 1999], the propositions were reorganized into seven axioms as follows:

- The Centrality Axiom states that *central to all systems are two pairs of propositions: emergence and hierarchy, and communication and control*. The centrality axiom's propositions describe the system by focusing on (1) a system's hierarchy and its demarcation of levels based on emergence and (2) systems control which

Table V. Alphabetical Listing of Systems Propositions

Proposition and Primary Proponent	Brief Description of the Systems Proposition
Circular causality (Korzybski, 1994)	An effect becomes a causative factor for future effects, influencing them in a manner particularly subtle, variable, flexible, and of an endless number of possibilities.
Communication (Shannon, 1948a, 1948b)	In communication, the amount of information is defined, in the simplest cases, to be measured by the logarithm of the number of available choices. Because most choices are binary, the unit of information is the *bit*, or binary digit.
Complementarity (Bohr, 1928)	Two different perspectives or models about a system will reveal truths regarding the system that are neither entirely independent nor entirely compatible.
Control (Checkland, 1993)	The process by means of which a whole entity retains its identity and/or performance under changing circumstances.
Darkness (Cilliers, 1998)	Each element in the system is ignorant of the behavior of the system as a whole, it responds only to information that is available to it locally. This point is vitally important. If each element 'knew' what was happening to the system as a whole, all of the complexity would have to be present in that element (Cilliers, 1998).
Dynamic equilibrium (D'Alembert, 1743)	For a system to be in a state of equilibrium, all subsystems must be in equilibrium. All subsystems being in a state of equilibrium, the system must be in equilibrium.
Emergence (Aristotle, 2002)	Whole entities exhibit properties which are meaningful only when attributed to the whole, not its parts – e.g. the smell of ammonia. Every model of systems exhibits properties as a whole entity which derive from it component activities and their structure, but cannot be reduced to them (Checkland, 1993).
Equifinality (Bertalanffy, 1950a)	If a steady state is reached in an open system, it is independent of the initial conditions, and determined only by the system parameters, i.e. rates of reaction and transport.
Feedback (Wiener, 1948)	All purposeful behavior may be considered to require negative feed-back. If a goal is to be attained, some signals from the goal are necessary at some time to direct the behavior.
Hierarchy (Pattee, 1973)	Entities meaningfully treated a wholes are built up of smaller entities which are themselves wholes . . . and so on. In a hierarchy, emergent properties denote the levels (Checkland, 1993).
Holism (Smuts, 1926)	The whole is not something additional to the parts: it is the parts in a definite structural arrangement and with mutual activities that constitute the whole. The structure and the activities differ in character according to the stage of development of the whole; but the whole is just this specific structure of parts with their appropriate activities and functions (Smuts, 1926).
Homeorhesis (Waddington, 1957, 1968)	The concept encompassing dynamical systems which return to a trajectory, as opposed to systems which return to a particular state, which is termed homeostasis.
Homeostasis (Cannon, 1929)	The property of an open system to regulate its internal environment so as to maintain a stable condition, by means of multiple dynamic equilibrium adjustments controlled by interrelated regulation mechanisms.
Information Redundancy (Shannon & Weaver, 1949)	The number of bits used to transmit a message minus the number of bits of actual information in the message.
Minimum Critical Specification (Cherns, 1976, 1987)	This principle has two aspects, negative and positive. The negative simply states that no more should be specified than is absolutely essential; the positive requires that we identify what is essential.

Table V. Continued

Proposition and Primary Proponent	Brief Description of the Systems Proposition
Multifinality (Buckley, 1967)	Radically different end states are possible from the same initial conditions.
Pareto (Pareto, 1897)	Eighty percent of the objectives or outcomes are achieved with twenty percent of the means.
Purposive Behavior (Rosenblueth, Wiener, & Bigelow, 1943)	Purposeful behavior is meant to denote that the act or behavior may be interpreted as directed to the attainment of a goal-i.e., to a final condition in which the behaving object reaches a definite correlation in time or in space with respect to another object or event.
Recursion (Beer, 1979)	The fundamental laws governing the processes at one level are also present at the next higher level.
Redundancy (Pahl, Beitz, Feldhusen, & Grote, 2011)	Means of increasing both the safety and reliability of systems by providing superfluous or excess resources.
Redundancy of Potential Command (McCulloch, 1959)	Effective action is achieved by an adequate concatenation of information. In other words, power resides where information resides.
Relaxation Time (Holling, 1996)	Stability near an equilibrium state, where resistance to disturbance and speed of return to the equilibrium are used to measure the property. The system's equilibrium state is shorter than the mean time between disturbances.
Requisite Hierarchy (Aulin-Ahmavaara, 1979)	The weaker in average are the regulatory abilities and the larger the uncertainties of available regulators, the more hierarchy is needed in the organization of regulation and control to attain the same result, if possible at all
Requisite Parsimony (Miller, 1956)	Human short-term memory is incapable of recalling more than seven plus or minus two items (Simon, 1974).
Requisite Saliency (Boulding, 1966)	The factors that will be considered in a system design are seldom of equal importance. Instead, there is an underlying logic awaiting discovery in each system design that will reveal the saliency of these factors.
Requisite Variety (Ashby, 1956)	Control can be obtained only if the variety of the controller is at least as great as the variety of the situation to be controlled.
Satisficing (Simon, 1955, 1956)	The decision making process whereby one chooses an option that is, while perhaps not the best, good enough.
Self-organization (Ashby, 1947)	The spontaneous emergence of order out of the local interactions between initially independent components.
Suboptimization (Hitch, 1953)	If each subsystem, regarded separately, is made to operate with maximum efficiency, the system as a whole will not operate with utmost efficiency.
Viability (Beer, 1979)	A function of balance must be maintained along two dimensions: (1) autonomy of subsystem versus integration and (2) stability versus adaptation.

requires feedback of operational properties through communication of information.

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

The specific axiom and its supporting propositions are presented in Table VI. It is important to note that neither propositions nor their associated axioms are independent of one another.

3.4. Construct for Systems Theory

Systems theory provides explanations for real-world systems. These explanations increase our understanding and provide improved levels of explanatory power and predictive ability for the real-world systems we encounter. Our view of systems theory is a model of linked axioms (composed of constituent propositions) that are represented through similarity to the real system [Giere, 1988]. Figure 3 is a construct of the axioms of systems theory. The axioms presented are called the "theorems of the system or theory" [Honderich, 2005] and are the set of axioms, presumed true by systems theory, from which all other propositions in systems theory may be induced.

Systems theory is the unified group of propositions, linked with the aim of achieving understanding of systems. Systems

Table VI. Axioms for Systems Theory

Axiom	Proposition and Primary Proponent
Centrality	Communication (Shannon, 1948a, 1948b)
	Control (Checkland, 1993)
	Emergence (Aristotle, 2002)
	Hierarchy (Pattee, 1973)
Contextual	Complementarity (Bohr, 1928)
	Darkness (Cilliers, 1998)
	Holism (Smuts, 1926)
Design	Minimum Critical Specification (Cherns, 1976, 1987)
	Pareto (Pareto, 1897)
	Requisite Parsimony (Miller, 1956)
	Requisite Saliency (Boulding, 1966)
Goal	Equifinality (Bertalanffy, 1950a)
	Multifinality (Buckley, 1967)
	Purposive Behavior (Rosenblueth, et al., 1943)
	Satisficing (Simon, 1955, 1956)
	Viability (Beer, 1979)
Information	Redundancy of Potential Command (McCulloch, 1959)
	Information Redundancy (Shannon & Weaver, 1949)
Operational	Dynamic equilibrium (D'Alembert, 1743)
	Homeorhesis (Waddington, 1957, 1968)
	Homeostasis (Cannon, 1929)
	Redundancy (Pahl, et al., 2011)
	Relaxation Time (Holling, 1996)
	Self-organization (Ashby, 1947)
	Suboptimization (Hitch, 1953)
Viability	Circular causality (Korzybski, 1994)
	Feedback (Wiener, 1948)
	Recursion (Beer, 1979)
	Requisite Hierarchy (Aulin-Ahmavaara, 1979)
	Requisite Variety (Ashby, 1956)

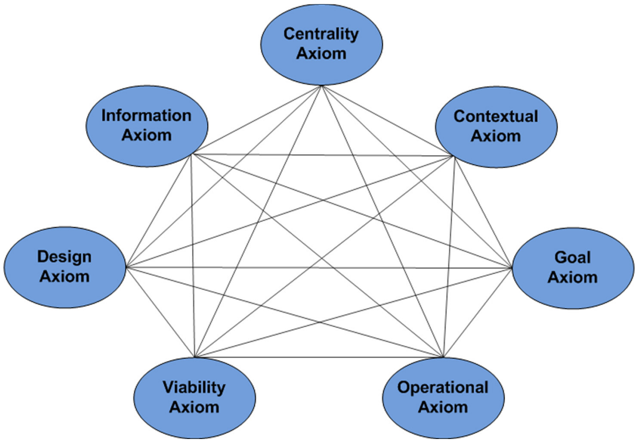

Figure 3. Axioms of systems theory. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

theory, as proposed in this paper, will permit systems practitioners to invoke improved explanatory power and predictive ability. It is precisely this group of propositions that enables thinking, decision, action, and interpretation with respect to systems.

The axiom set in Figure 3 may be considered a construct of a system, where a construct is defined as a characteristic that cannot be directly observed and so can only be measured indirectly [Bernard, 2002; Gliner and Morgan, 2000; Leedy and Ormrod, 2001; Orcher, 2005] and a system is defined as "...a set of interrelated components working together toward some common objective or purpose" [Blanchard and Fabrycky, 2006: 2]. Thus, a system may be identified as such if it exhibits and can be understood within this set of axioms. Conversely, any entity that exhibits these seven axioms is, by definition, a system. Thus, given its testable nature, this construct can be evaluated with respect to systems under consideration in order to determine its generalizability. Further, given the multidisciplinary nature of its foundational axioms and the multidisciplinary nature under which the construct was formed, there are numerous implications for multidisciplinary application of such a construct.

4. MULTIDISCIPLINARY IMPLICATIONS OF SYSTEMS THEORY

We have presented a construct for systems theory, proposed a set of seven axioms and group of supporting propositions from the 42 fields of science. Our construct for systems theory is the unified group of propositions, linked by an axiom set that aims to achieve understanding of systems that provides improved explanatory power and predictive ability. It is precisely this group of propositions that enables thinking, decision, action, and interpretation with respect to systems.

We believe that systems theory is the foundation for understanding multidisciplinary systems. Practitioners can benefit from the application of systems theory as a lens when viewing multidisciplinary systems and their related problems. Systems theory and the associated language of systems are important enabling concepts for systems practitioners. The set

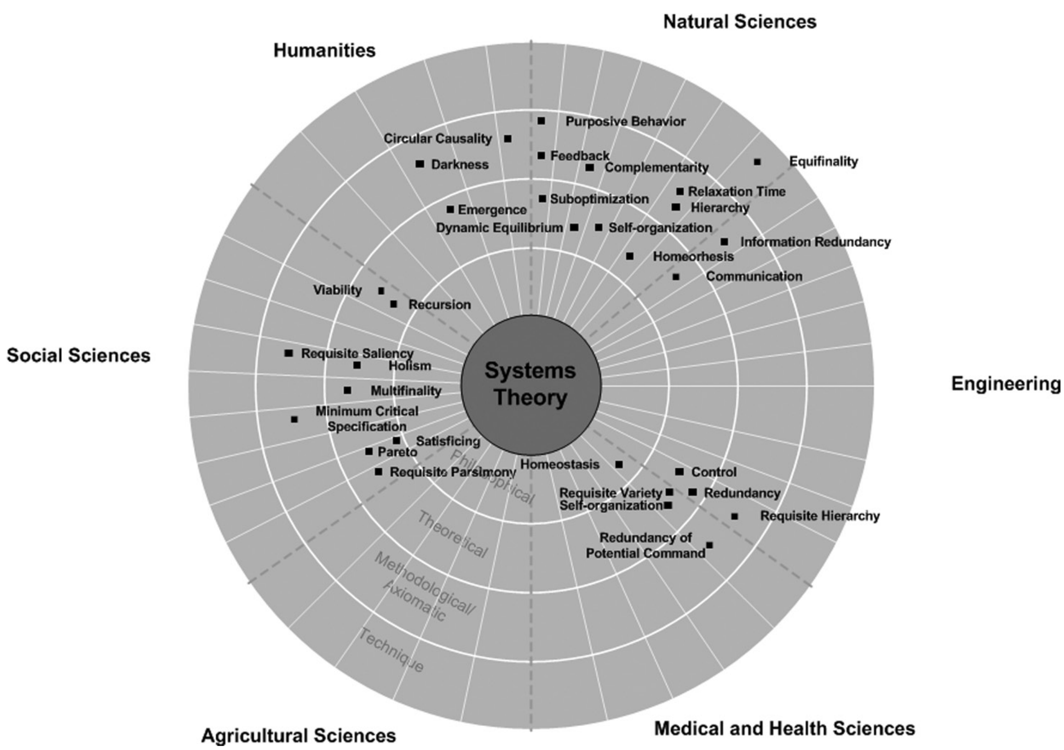

Figure 4. Systems theory and the major fields of science.

of seven framework axioms and associated group of propositions that we designate as systems theory allow systems practitioners to ground their observations to a rigorously developed systems-based foundation.

Behaviors expected from systems should be described by the axioms proposed in this paper. For example, any system should exhibit suboptimization. For a system as complex as a Boeing 747, this means trade-offs between increased cargo carrying capacity and maximum airspeed, whereas a simpler system such as a laptop computer may require that the heating system be suboptimal (i.e., larger than ideal) in order to support a faster processing chip. While this simply illustrates the use of one of the propositions described herein, each axiom and its associated propositions provides insight into the behavior of the system. Understanding of the proposed construct of systems theory affords systems practitioners greater overall system understanding.

Finally, the propositions from the seven axioms, described briefly in Table V, can be superimposed on the Depiction of Knowledge and the Fields of Science presented in Figure 1. Figure 4 presents systems theory as the intersection of a number of well-defined multidisciplinary propositions by distinguished authors from the 42 fields of science.

It is clear from viewing Figure 4 that systems theory and its theoretical foundation are inherently multidisciplinary. Contributions to our perspective of systems theory are incorporated from each of the major fields of science with the exception of agricultural sciences (most probably due to the *darkness* proposition). This multidisciplinary construct ensures widespread applicability of this theory and removes barriers that traditional engineering-centric views of systems place on approaches to problem solving. The lack of a prescription regarding domain applicability further ensures that systems theory is multidisciplinary in both its theoretical foundations and application.

5. CONCLUSION

We have proposed systems theory as a unified group of specific propositions which are brought together by way of an axiom set to form the construct of a system. This construct affords systems practitioners and theoreticians with a prescriptive set of axioms by which the system operation can be understood; conversely, any entities identified as a system may be characterized by this set of axioms. Given its multidisciplinary theoretical foundation and multidisciplinary framework, systems theory, as developed in this paper, is posited as a general approach to aid in understanding system behavior. This formulation is in its embryonic stages and would be well served from feedback and challenge from systems practitioners to test this proposed construct and encourage future development of systems theory as a coherent, multidisciplinary endeavor.

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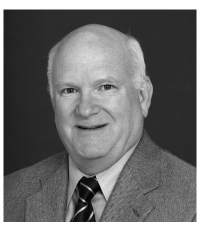

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