# About Teaching Systems Thinking

James J. Kay
Environment and Resource Studies
University of Waterloo

Jason A. Foster
Systems Design Engineering
University of Waterloo

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**Abstract**

This paper discusses the introductory teaching of systems thinking. It puts forth an approach that emphasizes the application of systems thinking in real world settings. This approach focuses on five major elements of systems thinking; system studies, general systems behaviour, complexity, general systems tools, and systems approaches (methodologies), as well as the issues of design, synthesis, epistemology and ontology. Finally, the role of traditional discipline-based education in the context of teaching systems thinking is considered.

## 1. Introduction

Systems thinking is largely a post World War II phenomena, although the early work of von Bertalanffy was done between the two world wars. In the past fifty years, the popularity and perceived importance of systems thinking has waxed and waned. During the heyday of the US space programme, systems thinking was immensely popular. The failure of systems simulation and modelling to deliver on their promises, combined with the advent of neo-conservatism in the late 1970s, cause systems thinking to enter a quiescent period. The rising interest during the last decade in information technology, chaos theory, and complexity has sparked a resurgence of interest in systems thinking.

As systems thinking is, by its nature, transdisciplinary and synthetic, it does not fit well within the disciplinary and analytical model of knowledge that is the backbone of modern education systems. This disparity, combined with Systems' waxing and waning in popularity, has meant that there are relatively few isolated pockets of systems education. Few text books exist and even fewer programmes[1]. This leaves those interested in systems education with a dearth of resources and the necessity of largely inventing their own material.

The challenge of sustainability that faces our species is fundamentally about dealing with complexity and systems [1, 2, 3]. There are those who have argued that the situation we find ourselves in is a consequence of the inability of normal disciplinary science to deal with systems issues. [4] The development of a systems based

[1] Probably the oldest programme in systems thinkingis the graduate "Program of Research in Interdisciplinary Systems Management" established by von Bertalanffy at the University of Ottawa. Systems Design Engineering and Environment and Resource Studies are two systems-based departments at University of Waterloo. Open University in England has had a long running programme in systems thinking, as do several other British institutions.

approach to resolving the ecological socio-economic dilemmas we face is of paramount importance. Thus there is some urgency to the need for systems education.

In this paper we report on the experience of teaching introductory courses in systems thinking both in engineering and in an environmental studies programme that emphasises sustainable development.

## 2. What Is Systems Thinking?

There are as many definitions of the field of systems thinking as there are systems thinkers. This lack of formal definition affects everything in systems from the basic terminology, for example *system* and *boundary*, to the higher level concerns of systems practice and systems education. Given systems inherent relativism and acknowledgment of multiple valid perspectives, attempts to develop formal definitions in the field may be impossible, and probably undesirable. This has not, however, stopped the attempts [5, 6].

This paper takes the pragmatic position that a reflexive definition of systems thinking is most useful. We take systems thinking to be made up of the beliefs and perspectives embodied by the disciplines and practices that claim to embody systems thinking. This definition allows discussion to proceed along functional lines, as opposed to being encumbered with philosophical, epistemological, or ontological issues. While such issues are important and worthy of discussion, the nature of systems means that there can be no end to such discussions.

The reflexive definition of systems thinking embodies a number of branches of the system tree including: Systems Thinking [7], System Dynamics [8], Systems Engineering [9], Systems Behaviour [10], General System Theory [11], and Systems Design Engineering [12]. For the most part, these branches have adopted compatible core beliefs and perspectives.

Generally speaking, systems thinking is about the study of objects as wholes. Koestler [13] noted that systems thinking is two faced (Janus). On the one hand it examines an object as being composed of systems and on the other hand it deals with an object as a whole situated in a bigger system (environmental context). Thus systems thinking is both reductionist and holistic, that is hierarchical [14, 15]. The study of hierarchy theory has become an important aspect of systems thinking.

Systems thinking studies the way in which wholes and context give rise to emergent properties. It also examines how the whole is made up of the processes and structures which define it. These processes and structures are studied in terms of inputs, outputs, transformations, and interconnections between the components which make up the system. Systems are also studied in terms of their states. Feedback loops and cybernetics plays a key role in this regard. A number of common properties and behaviours of systems have been identified and it is these generalizations which give systems thinking its power.

In short systems thinking is about synthesising together all the relevant information we have about an object so that we have a sense of it as a whole.

The reader should be aware that systems thinking is often confused with other notions. *Systematic thinking* refers to thinking in a rigorously defined, methodological manner.

*Interdisciplinary research* is about bringing more than one discipline to bear on an issue. *Holistic thinking* refers to thinking about wholes, not simply parts. *System Dynamics* refers to temporal simulation models of systems. Programming simulation tools, such as Stella, is often thought to be synonymous with systems thinking. And of course there is the ever present association of "systems" with "computers". While all of these notions are aspects of systems thinking, each is only minor facet of a multi-faceted enterprise.

Two other terms that occur commonly in the systems literature are "hard" and "soft" systems. Hard systems contain "…easy-to-define objectives, clearly defined decision-taking procedures and quantitative measures of performance." Whereas in soft systems "… objectives are hard to define, decision-taking is uncertain, measures of performance are at best qualitative and human behaviour is irrational." [5] Ironically hard systems refers to the study of situations which are easy to understand, even though they may be complicated, and for which hard answers are possible. Soft systems, on the other hand, refers to situations which are difficult to understand, are dominated by complexity, and for which only soft answers are possible. Systems thinking applies to both types of system.

## 3. An Approach to Teaching Systems Thinking

A simple, general description of teaching consists of three aspects. First, there is the content which the student is expected to learn. The term "content" refers to all of information, not simply the material taught during formal instruction. The second aspect is the methods and methodologies used to impart the content to the student. Lectures, "self-directed learning", assignments, etc. fall under this rubric. The final aspect is acceptance. This refers to the willingness on the part of the student, teacher, and wider community to accept the content, methods, and methodologies being used.

Systems educators, charged with teaching a relatively new and poorly defined field, are currently focused primarily on developing content, method, and to a lesser extent methodologies. Developing more detailed methodologies and promoting the acceptance of systems thinking will gain in importance as the discipline moves further into mainstream education.

A simple linear method for of teaching systems thinking is as follows:

1. Promote interest in the student by demonstrating the insights systems thinking offers;
2. Explain the circumstances in which systems thinking applies;
3. Provide individual systems thinking tools that can be applied to a wide variety of systems problems;
4. Introduce the various perspectives and approaches that make up systems thinking;
5. Integrate the tools and approaches into a comprehensive systems thinking perspective; and,
6. Allow the student to practice systems thinking in the real-world context.

This method is similar to one proposed for teaching the Soft Systems Methodology [16].

Students studying systems thinking need to learn about five major elements of systems thinking. The first of these elements is about the exercise of performing a system study. This involves identifying the system to be investigated and its important behaviours. Another important element, isomorphism, was identified by von Bertalanffy as a cornerstone of general systems thinking. This involves teaching about general tools for describing and analysing systems, tools which apply across disciplines and to a broad class of systems. A third element related to isomorphism is general systems behaviour. This involves teaching students about such phenomena as non-linear behaviour and attractors, feedbacks, emergence, self-organization and chaos. The next element is complexity or the notion that systems thinking is about middle number systems. Finally students must learn about systems approaches, methodologies for using systems thinking to deal with real world issues

The remaining sections of this paper discuss this content in the sequence suggested by the six step method above.

## 4. System Studies

Systems thinking is primarily an applied field. Students must be given explicit opportunities to apply systems tools and approaches to real-world situations. Doing so allows the student to synthesize their own definition of systems thinking, to understand the differences in applying heuristics, and to experience irreducible complexity first hand. The first vehicle for this is the system study.

A system study involves identifying the system to be investigated and its important behaviours. It involves identifying the purpose of the study, hierarchy (i.e. scale, type and nesting), important processes and structures, elements and their interconnections, particularly feedbacks, the environmental context for the system and the important behaviours of the system. What should emerge from a system study is a framing of the situation being examined, so that meaningful questions can be asked about it.

Experience has shown that students can only really appreciate systems thinking and the issues related to it after they have undertaken a system study. Accordingly it must be the first element of a systems education. The approach to introducing systems studies is two pronged, involving both in class examples and student-driven system studies.

Examples which are done in a lecture setting should be directly related to the students' experiences. They should focus on issues that students are concerned about. Through the examples done in class, students should gain new insights into the situation under discussion. This is crucial to the success of teaching systems as it promotes student interest by demonstrating the insights systems thinking offers

The examples should also be structured so that each one introduces some new system concepts and builds on the concepts from the previous example. The examples are about teaching both concept and method and motivating student interest in the topic.

Students should be assigned in small groups to undertake their own system study and present it to the class. Small groups are important. The students will very quickly realize that even though they are looking at the same situation, they have quite different perspectives on it. The system study provides a systematic tool for identifying, integrating and resolving these different perspectives. In this way it acts as a boundary object. [17]

The system study must be about something of real importance to the students. We suggest that the object of focus be related to a project that is being undertaken in another setting by the students. This serves two purposes. The students already have background on the object of focus, saving them significant background research time. More importantly, they usually gain significant new insights about the project they are undertaking in another context, thus demonstrating to the students, in a very vivid manner, the relevance of systems thinking.

## 5. General Systems Behaviour

Ludwig von Bertalanffy, popularly considered the founder of systems thinking, wrote “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.” [11] von Bertalanffy was describing the need for general theories that apply across disciplines and to a broad class of systems. Such theories can be classified as transdisciplinary or isomorphic. Take for example catastrophe theory. This theory can be applied to and provide insights about change in political systems, ecological systems, animal behaviour systems, mechanical structures and other systems. Catastrophe theory describes a set of behaviours which are isomorphic to a wide variety of systems and hence are referred to as general systems behaviours. Other examples of theories which describe general systems behaviours are cybernetics, group theory, self-organization theory, and chaos theory.

Traditional Western science holds to certain fundamental beliefs, in particular the universal applicability of linear models, Ockham’s Razor, and Newtonian reductionism. Western education has incorporated these beliefs both implicitly and explicitly, such that by the end of high school even those students who avoided the sciences have been indoctrinated. Educating students about general systems behaviours involves teaching them about such phenomena as non-linear behaviour, attractors and flips between attractors, feedbacks, emergence, self-organization and chaos. Generally these behaviours are not intuitive to students, as they do not conform to the Newtonian linear causality mode of reasoning that is a cornerstone of our culture.

Students must be given hands on experience with a variety of systems which exhibit such phenomena. This allows them to build up the gut intuitive feel that they need to understand these phenomena and a sense of the generality of the behaviours. There are numerous physical examples which can be used in the classroom and lab with which students can interact directly including the double-pendulum, vortex generators [18], and Bénard cells. Play should be encouraged. Stella can also be a useful tool in this regard. [19] However simulation models cannot replace hands on experience, they can only augment it.

Providing prospective students of systems with hands on experience interacting with systems which exhibit nonlinear/emergent/catastrophic and chaotic behaviour is one way to instill in them the desire to learn about systems thinking. Such examples pose a direct challenge to the student's existing beliefs about how the world works, and such challenges can promote interest in the richer understanding that systems thinking offers.

At this stage in the systems thinking education the goal is to promote an appreciation of the generality of system theories and promote the development of a new intuition in the students. This intuition is that the world is a much more complex place than previously believed and that there is a need for these phenomena to be understood, not swept under the rug of linearity and reductionism. The instruction about general systems behaviour is not intended to provide the students with analytical tools; such tools follow naturally later. However usually at this stage a more pressing issue for the student is developing a feel for the nature of complexity.

## 6. Complexity

Systems thinking provides both a new perspective and new tools which can be brought to bear on problems. It is not, however, a universally applicable panacea. The early systems thinkers realized that the general behaviours they were observing occurred in circumstances which were limited and that the techniques they were developing were too complex for some situations and too simple for others.

Weinberg [20], following on the work of Weaver [21], proposed the partitioning of problem situations based on their complexity and level of randomness. Organized (not random), simple situations, with small numbers of interactions, are designated "small-number" problems. They are the purview of Newtonian science and mechanistic explanation. Highly unorganized complex situations, dominated by large numbers of random interactions and aggregate behaviour, are designated "large-number" problems. They are the purview of statistics. The remaining middle ground, with intermediate numbers of interactions, and organized complexity with only a degree of unpredictability, are designated "middle-number" problems. It is these middle number situations to which systems thinking is most applicable. This idea of partitioning problem situations based on complexity and organization is key to understanding the domain of applicability of systems thinking.

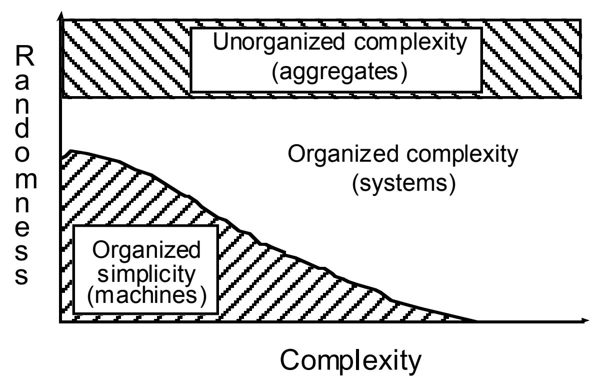


**Figure 1 – Weinberg's Problem Situation Partitioning**

Over the past two decades, a number of new insights, that go well beyond those of general systems theory, have emerged from the study of adaptive, self-organizing complex systems and the field of chaos theory. Together these insights are referred to as complex systems theory [22]. Some of these insights follow.

The hierarchical nature of complex systems requires that they be studied from different types of perspectives and at different scales of examination. There is no correct perspective. Rather a diversity of perspectives is required for understanding. By their nature such systems are self-organizing. This means that their dynamics are largely a function of positive and negative feedback loops. This precludes linear causal mechanical explanations of their dynamics. In addition emergence and surprise are normal phenomena in systems dominated by feedback loops. Inherent uncertainty and limited predictability are inescapable consequences of these system phenomena. Such systems organize about attractors. Even when the environmental situation changes, the system's feedback loops tend to maintain its current state. However, when system change does occur, it tends to be very rapid and even catastrophic. When precisely the change will occur, and what state the system will change to, are often not predictable. Often, in a given situation, there are several possible system states (attractors), that are equivalently likely. Which state a system currently occupies is a function of its history. There is not a “correct” preferred state for the system. These insights demand a rethinking of the epistemology of inquiry and are at the heart of the rationale for modern systems thinking, an activity which is quite different from the normal science of “small number” problems. [14, 15, 23, 24]

Discussing complexity with students interested in pursuing systems thinking builds on the intuition developed in discussing general systems behaviours. It provides them with two valuable insights. The first insight is that an investigator must consciously decide which techniques to apply to solve particular problems. This insight leads the student to recognize systems thinking as a pragmatic activity that accepts its own strengths and limitations.

The second, and more important insight brought about by teaching complexity is epistemological in nature. Accepting the existence of complexity, in particular the irreducible complexities that lie at the heart of many synergistic systems, promotes a new epistemological stance. We must deal with irreducible uncertainty, emergence and surprise, the lack of a preferential perspective, and the reality that life is a tradeoff. We no longer have the luxury of dealing with problems for which reductionist “scientific method” approaches are sufficient and predictability and the ability to anticipate are the hallmark of success. This epistemological stance, demanded by the realities of “middle number” systems, is what differentiates systems approaches from approaches which are merely systematic or holistic.

## 7. General Systems Tools

All fields and disciplines have essential tools that are required of their practitioners. Systems theory is no exception and a number of tools for systems analysis (describing an object as a system and describing the system behaviour) and systems design have been extensively developed. Examples of these tools include network thermodynamics (e.g. graph theoretic descriptions of physical flow systems), information theory, pattern recognition, group theory, statistics, stability (catastrophe) theory, cybernetics, causal loop analysis, and self-organization theory.

Tools such as information theory and statistics are taught to many individuals in mathematics, engineering and the social sciences. Following on the idea of isomorphism, systems thinking differs from these disciplines by proposing that these tools can be applied across a broad range of problems. Take for example network thermodynamics a.k.a. graph theoretic modelling. It is applicable to any system involving physical flows. It has been applied equally well to the design of solar energy systems, electrical networks, city water works, computer chips, and pharmaceutical behaviour in the human body. When introducing these tools in a systems thinking context, it is important both to emphasize and demonstrate that the tools apply to a broad category of systems and problems.

It must be mentioned that many of these tools require significant mathematical background on the part of the student. In fact each merits at least a course in its own right as part of an education in systems thinking. However in an introductory context, some examples of the broad domain of applicability of these tools and the insights gained from their use suffices to motivate further investigation by students

## 8. Systems Approaches

A set of tools acquires value when wielded together with a specific purpose in mind. Systems thinking, with its isomorphic tools and concept of complexity, is an academic curiosity if it does not provide us with insights and methods for dealing with human concerns. Historically "system approaches", referred to methodologies for problem solving and design. Hard-systems problems, such as the space programme, have been solved with success using problem solving techniques such as Systems Engineering and Operations Research.

However, as we have begun to deal with complex issues such as the environment, ecological economics, and information technology, weaknesses in the hard systems methodologies have become evident. The techniques of hard-system problem solving are not well suited to situations were organizational flux and uncertainty dominate as these tools presuppose well structured predictable situations. In these soft-systems situations the risks, uncertainties, and potential benefits inherent in the situation are all high. In fact characterizing the undertaking of dealing with such situations as "problem solving" is too limited a description [5]. Rather it is about methods for framing situations and identifying and resolving tradeoffs related to technology, societies, economics, people and the environment, under conditions of irreducible uncertainty. In the post-modern world, hard-systems problems are the central issues of the past and soft-systems situations are the key concerns of the future.

There are few soft-systems approaches. Students of systems thinking must be made aware of the tools that do exist, such as Checkland's Soft Systems Methodology [5, 25, 26, 27].

Whether dealing with soft or hard systems situations, instruction about systems approaches is best done in the form of case studies, both presented in class and undertaken as student projects. In this regard, we can not overstate the importance of students participating in project work. One cannot learn to drive a car or to ride a bicycle by attending lectures or watching others doing it. One must do it oneself under the guidance of an experienced practitioner. Learning about systems approaches is learning a craft and as such the apprenticeship model is the appropriate mode of instruction.

Students of systems thinking must realize that all systems approaches are heuristics that must be interpreted and adapted on a case-by-case basis. Students must learn to build their own tool kit and which tools are appropriate in particular contexts. This methodological flexibility is foreign to those brought up to believe in the scientific method, but it is vital to the successful practice of systems thinking.

## 9. Synthesis

Education about systems approaches does not fit well with classic disciplinary education where the focus is on analysis. Systems thinking is necessarily about analysis, but also about design and synthesis, aspects which require a fundamentally different approach to teaching.

In modern undergraduate education, especially in engineering, the synthesis of knowledge is something that happens outside of the classroom. The breadth of a modern engineering education is such that classroom time is spent introducing individual concepts and solving contrived examples. Unless the program includes capstone design courses or courses that address synthesis directly, a student's synthesized understanding develops solely through personal epiphanies.

The challenge of a systems education is to teach students not just how to analyse a situation from a disciplinary perspective but how to synthesize the insights gained from several disciplinary analyses into an overall understanding that leads to action. Fundamental pedagogical shifts, such as to the use of project-based learning, are required to meet this challenge.

Systems thinking itself can also be considered and taught as a synthesis. The flexibility and fluidity inherent in the practices of systems thinking allows its practitioners to develop individual interpretations of the systems techniques, tools, approaches, and methodologies. Students of systems thinking should be encouraged to develop their own syntheses of these topics and to create their own understanding of systems thinking.

## 10. The Role of Disciplines

There is much debate over the relationship between specific disciplinary skills and the isomorphic skills of systems thinking in the context of education. The question underlying the debate is whether systems thinking can be taught without the foundation of specific disciplinary skills. One camp holds that the specific must be taught before the general. Traditional engineering education follows this model. The other camp holds that many of the benefits of systems thinking can be realized from general knowledge. In this case the more specialized knowledge, with it inherent codified perspective and assumptions, may be a hindrance to the successful application of systems thinking.

Systems thinking gains much of its value from the different perspectives it brings, the questions it asks, and the assumptions it questions. These aspects of systems thinking can be explained without the need for specific background skills, such as higher mathematics. That having been said, it is very difficult for investigators to take a factor into account if they either unaware of its existence or unable to incorporate it into their conception of the world.

The successful practice of systems thinking requires knowledge at both the systems-level and the discipline-level. Ideally a single individual would possess sufficient knowledge at both levels to address the issues at hand. As system complexity rises, this become increasingly difficult. Instead of an individual, a team is required, composed of both disciplinary specialists and systems thinkers. However both need to know enough about the other to function together as a team. The point is that one needs to strike a balance between disciplinary and systems thinking.

## 11. Conclusions

Systems thinking remains a niche discipline. While it is practiced by a wide variety of individuals in a wide variety of fields, it is still a difficult subject to teach. This difficulty has in large part been caused by the adoption of traditional teaching models that emphasize disciplinary analysis. These are poorly suited to teaching the very different mindset that systems thinking entails. The development and refinement of systems-specific teaching methods is required if systems thinking is to break out of its niche and become a central part of modern education, something which is necessary if we are to deal with the complexity around us.

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