Teaching Complexity and Systems Thinking to Engineers

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The mid-1990s saw the resurgence of the notions of complexity and systems thinking. Within engineering the fields of nonlinear dynamics and stability theory, both aspects of complexity, have developed thriving communities. Softer areas, such as 2nd order cybernetics, are being shared with schools of business and management. As complexity and systems concepts become integrated into the practice of engineering they must also become more central to engineering curriculum.

INTRODUCTION

As our technical knowledge grows so to does the scope of the problems being addressed by engineers. Where engineers once dealt primarily with immediate issues, such as structural soundness, they are now responsible for addressing wider issues such as environmental impact, aesthetics, and urban sprawl. Problems once perceived as being simple are now revealing new complexities as our perceptions and abilities evolve and progress.

The Department of Systems Design Engineering at the University of Waterloo was founded in 1968 with the explicit goal of training engineers to be able to address these complexities. To accomplish this goal the founders of the Department developed a philosophy and curriculum that has remained unique among Canadian engineering programmes. The core of the Department's unique flavour has been, and remains, a focus on design and systems. Design is a core activity within engineering and has been discussed by many prominent engineers [8]. The formal concept of a system is a new topic for many engineers.

It must be emphasised that Systems Design Engineering is not systems engineering as described by Sage [10]. While the lifecycle approach that lies at the heart of systems engineering may be used by a Systems Design Engineer, the core premises and beliefs of the two disciplines are different and distinct.

COMPLEXITY AND SYSTEMS THINKING

The field of study that contains the formal concept of a system is relatively new and continues to define itself. As such mapping the boundaries of the field is relatively difficult. At the 2000 conference of the International Society for the Systems Sciences (ISSS) the topics discussed ranged from computer programming and characteristics of the Hamiltonian equation through to postmodern thought and the effects of language on perception. Based on this breadth a pragmatic method of defining the boundaries of the field is to say that it includes any topic that uses the term 'system'.

The operational definition used by the Department considers a system to be a representation of an object. The object being represented need not be physical; abstractions and ideas may also be systems. The foci of the system representation are the object's function(s), process(es), structure(s), and interrelationships. The interrelationships may exist both within the system and between the systems and its environment.

When describing some situations the term 'system' is augmented with the adjective 'complex'. In much of the systems literature no distinction is made between regular systems and those that are complex. This lack of formal distinction is an artefact of the close linkages between these two distinct concepts. While both terms are extremely difficult to define in an unambiguous fashion, a simple heuristic is that systems concepts are a set of techniques used to address complex situations.

Operationally, a complex system is one where understanding requires the insights of different disciplines operating at different scales; where there is irreducible uncertainty; and, where there are multiple likely future states.

Systems concepts are found in a number of disciplines. The origins of the modern systems movement are generally traced to von Bertalanffy's 1940s work in evolutionary biology [14]. Early adopters of the systems ideas included Mead (anthropology), Gerard (physiology), Rapoport (mathematical biology), and Boulding (economics) [2,9]. While the concepts originated in fields associated with natural systems those researching mechanical and human systems quickly adopted them. Churchman and Beer linked systems concepts into operations research and organizational cybernetics while Wiener did so with cybernetics [1,4,]. In recent years, primarily through the work of Senge and Checkland, systems concepts have been integrated into the management sciences [3,11].

Ontology and Epistemology

The notions of systems and complexity were developed as a response to dissatisfaction with the science that dominated in the early 1900s. In the systems literature such science is commonly referred to as 'Newtonian'. Reflecting this description the philosophical underpinnings of Newtonian science are seen as including linearity, predictability, control, and the attainability of perfect knowledge.

During the 20th century a number of discoveries were made that questioned some of the philosophical assumptions of Newtonian science. In the domain of subatomic physics quantum mechanics demonstrated that predictability and perfect knowledge were unattainable. At the macroscopic level investigations into ecology, cybernetics, and solving the "3 Body Problem" revealed the limitations of treating complex systems in simple linear ways. The appreciation of positive feedback and the development of second order cybernetics nullified the notion of direct linear cause and effect. Finally, the use of computer simulation in attempts to predict the weather led to the discovery of chaos and its inherent unpredictability.

The systems literature tends not to distinguish between the science practiced by scientists and the popular conceptions of science. Many scientists, especially those in the pure disciplines such as physics, recognized immediately the significance of the scientific advances previously mentioned. However science it not exclusively the domain of the pure scientist. Policymakers and members of the general public also have conceptions of science. These conceptions can for the most part be labelled as Newtonian.

Coincident with the scientific challenges to the Newtonian worldview was the emergence in the mid-1900s of postmodernism. Based in the fields of literature and social criticism, the postmodern position is that no one worldview should be allowed to dominate any other without question. As Western secularism, by definition grounded in the Newtonian world view, grew to preeminence during the latter half 20th century it was subjected to postmodern critiques. This criticism, together with the impact of the aforementioned scientific discoveries, led to the development of a new science. This science, variously known as “The Science of Complexity”, “Post-Normal Science, or “Systems Science”, is still being developed and refined. Nevertheless a number of its core epistemological and ontological precepts can be identified.

Irreducible Uncertainty

At the core of the systems ideas is the ontological notion that the state of the universe is uncertain. This precept is analogous to the uncertainty principle of Heisenberg. Where Newtonian science views uncertainty as a surmountable issue of epistemology, systems science places uncertainty in an unassailable ontological position.

Bounded Rationality

Bounded Rationality is an epistemological variant of Irreducible Uncertainty. The essence of this precept is that our ability to understand the universe is inherently limited. The bounds also extend to the tools we create to assist our understanding.

Emergence

Emergence posits that once a system is sufficiently complex it will demonstrate behaviours that could not be predicted based on the behaviours of the system components. Once a behaviour has emerged it may be possible to explain it based on the component properties. A classic example of emergence is the wetness property of water, which cannot be predicted from the properties of hydrogen or oxygen.

Relativism and Perception

This precept posits that different observers will perceive a situation differently. Further no observer occupies a privileged position where their perception is considered to be more valid that that of any other. When coupled with Irreducible Uncertainty and Bounded Rationality, this precept leads to the conclusion that each of us has a different, equally valid, imperfect view of some portions of the universe.

Irreducible Complexity

Irreducible Complexity is an epistemological position that states that systems problems cannot be simplified without losing their essential nature. A common approach in the practice of Newtonian science is to discard outliers and higher order terms in equations. In many systems problems the outliers are of greater interest than the trends.

It is important to note that many problems or investigations can be completed successfully using the Newtonian worldview. Many of the discussions within the systems community focus on defining the contexts and problems best suited to the various approaches and worldviews. Weaver proposed a partitioning of problem situations based on the dimensions of randomness and complexity [16].

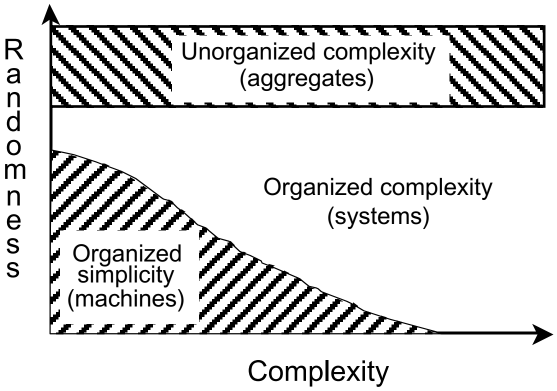

Figure 1 – Weaver's Partitioning of Problem Situations

The different regions of Figure 1 correspond to problems that are best suited to particular investigative techniques. Problems that lie within Organized Simplicity are best addressed using traditional Newtonian techniques. Statistical methods, such as statistical mechanics, apply best to those problems that lie within the region of Unorganised Complexity. The problems best suited to the techniques of Systems Science are those that exhibit Organized Complexity. Some of the characteristics of complex systems problems are as follows.

Nonlinear

Mathematical models of systems problems tend to be nonlinear. Such models are especially common when the components of the system are arranged in loops. These nonlinear systems exhibit characteristics such as sensitive dependence on initial conditions and multiple regions of stability. Such systems are complex in part because their behaviour is dependent not only on their current state but also on the path taken by the system over time; given only the current state it is not possible to predict the next state.

Middle Numbers

Weaver's partitioning of problems can be simplified, with some loss of effectiveness, by looking at the number of interactions present in the system. Using this characterisation Organized Simplicity would represent small number problems, Unorganised Complexity would represent large number problems, and Organized Complexity would represent middle number problems.

Relationships and Connectivity

The Middle Number characterisation does not take into account the nature of the relationships between the components. The type and arrangement of the relationships is as important as the quantity. These notions lead to questions regarding boundaries and identity that are central to the understanding of complex systems.

Tools and Applications

The disciplines that form the systems field have developed a number of tools to help address middle number problems. Examples of these tools include chaos theory, nonlinear dynamics, stability theory, control theory, and information theory. In addition to these fairly well known techniques, the systems field has also developed system dynamics and network thermodynamics. These techniques focus on modelling the connections present in complex systems.

Throughout much of its early history the systems field focused on manipulating mathematical models. Recently the focus has moved away from manipulating models towards the process of modelling. As opposed to developing solutions to problems based on mathematical models, the systems community is developing techniques to assist in framing situations and identifying and resolving tradeoffs under conditions of irreducible uncertainty.

ENGINEERING

The definitions of engineering commonly used in Canadian undergraduate programmes are all virtually identical. Colloquially, an engineer is “a person who uses science, mathematics and technology, in a creative way, to satisfy human needs.” [7] Discussions of engineering generally follow this definition with historical examples of engineering projects, a history of the evolution of the different engineering disciplines, and finish with discussions on professional behaviour. In general there is no discussion of the philosophy that underlies engineering.

A literature search reveals that while the philosophy of science has graduated to a research topic in its own right there has been little written on the philosophy of engineering. Certain authors, such as Petroski [8], do address philosophical issues. Philosophy enters their discussions in passing as they discuss the practice and history of engineering. The greatest concentration of research papers and courses on the topic of the philosophy of engineering can be found in Europe, in particular in the Eastern European nations.

Naively one could assume that engineers share the epistemological and ontological stances of the scientists who develop the tools that engineers apply. In this case engineers would share the Newtonian viewpoint that continues to dominate modern science. This approach neglects the central importance of design to engineering. Design can be seen as a complex process using the formal sense of the term. Some, and perhaps many engineers operate in circumstances where there is little or no proven theory, where there is much uncertainty, and where the projects are of sufficiently large scope that a single individual cannot encompass the complete solution. Operating under these circumstances requires that engineers adopt ontological and epistemological positions that are similar to those of systems science. The alternative approach of reducing the perceived complexity of the situation through assumptions and simplifications is no longer a viable option [13].

Two opposing forces are influencing engineering education. Once force is that of specialisation and scientific rigour. The second is the push for engineers who can cross disciplinary boundaries and deal with the problems of business and society. At the same time the practice of engineering is changing. As elucidated by Tenner, “… in controlling the catastrophic problems, we are exposing ourselves to more elusive chronic ones that are even harder to address." [13] The founders of the Department of Systems Design Engineering felt that introducing systems concepts to engineering would address these issues.

SYSTEMS PEDAGOGY

The curriculum used by the Department of Systems Design Engineering has been developed empirically over the last 30 years. When the Department was founded there was little formal research being done on the topic of engineering education. Excepting the work of Wankat [15] and a few others this situation remains largely unchanged. The lack of resources, coupled with a general academic unfamiliarity with the systems concepts, necessitated an empirical and evolutionary approach to curriculum design.

At a high level the curriculum has three overriding goals. First, systems design engineers should be able to reinterpret existing situations in ways that reveal new or previously hidden insights. Second, systems design engineers should be able to deal with engineering situations that are not dealt with by other specialist engineers. Finally, systems design engineers must be comfortable with the tools and terminology of other engineering specialists.

The students who enter the Department have been exposed almost exclusively to the Newtonian worldview. They do not question the validity of derivations or analytical techniques that share their assumptions. The systems-specific material covered by the Department calls these assumptions into question. Accordingly many students have difficulty accepting the validity the material. For the Systems Design curriculum to be effective it must move beyond presenting content and methodology. It must also promote the validity and applicability of the systems concepts and approaches.

Content and Methodologies

The Systems Design Engineering curriculum strives to cover a number of systems-specific topics. These topics include isomorphic tools, theories of complexity, general system behaviour, systems approaches, and systems studies. The following paragraphs discuss the idealised curriculum for each of these topics.

A key observation that led to the development of the systems ideas by von Bertalanffy was that systems in different disciplines and with dissimilar components exhibited similar behaviours. In von Bertalanffy's words, "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." [14] Von Bertalanffy was describing the need for general tools that apply across disciplines and to a broad class of systems. Such tools are deemed 'isomorphic' or 'transdisciplinary'.

Examples of isomorphic tools include graph theoretic modelling (sometimes referred to as network thermodynamics), information theory, pattern recognition, group theory, statistics, stability (catastrophe) theory, cybernetics, causal loop analysis, and autopoetic (self-organizing) theory.

Some of the isomorphic tools are taught in the pure sciences or in traditional engineering disciplines. For example electrical engineers are taught network thermodynamics in the guise of circuit theory. Systems thinking, and by extension the Systems Design curriculum, differs by proposing that these tools can be applied across a broad range of problems that span multiple disciplines. It must be emphasised that the successful application of transdisciplinary tools to problems in a particular discipline by necessity requires disciplinary knowledge. The more general tools offer different perspectives and insights, but they do not obviate the need for information from the specific problem context.

The second systems-specific topic is the theories of complexity. The term ‘complexity’, much like ‘system’, is extremely difficult to define. The Systems Design curriculum focuses on more mathematical definitions of complexity. The tools and terminology that are discussed come from the domain of stability theory, nonlinear systems, and chaos theory. Examples of the phenomena that are covered as part of this topic include nonlinear behaviour, attractors, tipping points, feedbacks, emergence, self-organization and chaos.

The third systems-specific topic is general system behaviour. Compared to the previous two topics this topic is significantly less formal and mathematical. The two main aspects of this topic are systems terminology and systems awareness. Basic systems terminology, including conceptual models and diagrams, is introduced to facilitate communication. After the terminology is introduced the students are encouraged to use it to describe their surroundings. The goal is for the students to develop an awareness of the breadth, depth, and scope of the systems perspective and field.

The introduction to general system behaviour also tries to evoke a sense of wonder and interest in the student. This is accomplished through history and demonstration. By virtue of being interdisciplinary, and in some ways subversive, the history of the systems movement includes a wide variety of interesting individuals. This history is presented to the students to gain their interest. Similarly some interesting systems phenomena can be demonstrated using fairly simple apparatus. Examples of these phenomena are chaos, in the form of a double pendulum, and self-organization, in the form of liquid vortices and Benard cells.

The fourth system-specific topic is system approaches. This topic moves away from particular analytical tools. Portions of the systems field, especially those areas concerned with ecosystems and human systems, focus more on process and methodology than on analytical or descriptive tools. Three such tools that are part of the Systems Design curriculum are Checkland’s Soft Systems Methodology (SSM), Jackson’s Critical Systems Thinking (CST), and Post-Normal Science (PNS) [3,5,6].

Much of the discussion regarding the systems approaches focuses on their heuristic nature. Many students have difficulty accepting that systems problems have no single right answer, if they have any answers at all. The systems approaches tend to exacerbate this difficulty by purposefully staying at a high level of abstraction. The systems practitioner is expected to adapt the approach to the particular context to which it is being applied. Discussions of the heuristic nature of the systems approaches tend to move into ethical and philosophical territories. For example the role of the expert is questioned, as are decisions about participation and legitimacy.

Possibly the most import topic raised during the discussions of the systems approaches is the so-called "halting problem". The systems perspective can lead students to the conclusion that everything is connected to everything. While in theory correct, this conclusion ignores the fundamentally pragmatic nature of the systems field. All of the systems tools and approaches exist to help a practitioner make sense of their situation. Ultimately the practitioner is responsible for deciding when sufficient detail has been captured and for halting the analysis at that point.

The final system-specific topic is system studies. Students are expected to apply the isomorphic tools, the theories of complexity, general system behaviour, and the system approaches to real situations. The students are expected to ask and attempt to answer questions related to systems concepts such as components, boundaries, hierarchy, and structure. The goal of this topic is for the student to discover how to go about framing a situation to address their needs. Issues that were discussed as theory are now dealt with in practice. The studies vary in terms of depth, breadth, and topic. In general the students are given the opportunity to choose the topics for their studies. Doing so helps to ensure that the student is interested in the work, which in turn tends to produce in increased enjoyment and superior results.

Organization

The Systems Design undergraduate curriculum is divided in core, technical elective, and complementary studies courses. Students are expected to complete 29 core courses, 6 technical electives, and 5 complementary studies. As Systems Design Engineering is an accredited Canadian engineering programme its curriculum must include a minimum amount of mathematics, basic and engineering sciences, and engineering design. The systems-specific material is generally covered either in specialised courses or as a part of engineering design.

Eight of the 29 core courses can be categorised as being systems-specific. Of these four cover isomorphic tools and general system behaviour.

- SD161 – Introduction to Systems Design Engineering
- SD252 – Linear Systems and Signals
- SD351 – Systems Models 1
- SD352 – Control Systems

The remaining four core systems-specific courses cover systems approaches and systems studies. They do so by providing design experiences for the students in which the systems perspectives can be used.

- SD361 – Introduction to Design
- SD361 – Systems Design Workshop 1
- SD461 – Systems Design Workshop 2
- SD462 – Systems Design Workshop 3

The Department offers approximately 40 technical elective courses per year. Of these four include systems-specific content.

- SD372 – Introduction to Pattern Recognition
- SD551 – Analysis of Large Systems
- SD554 – Systems Models 2
- SD761 – The Epistemology of Systems Thinking

Of all of the systems-specific courses SD161 and SD761 are the most comprehensive. SD761 in particular deals with the philosophical issues that are central to the systems field. While it is a graduate course, undergraduate students with sufficiently high academic standing have been permitted to attend for credit.

Teaching Techniques

Much of the Systems Design undergraduate curriculum is taught using traditional teaching techniques. Most courses are delivered through lectures and supplementary tutorials. While this format has the benefit of being familiar to the faculty and students, it does not provide many of the personal experiences that are central to promoting the acceptance of the systems ideas.

The workshop courses are taught using techniques that are more in keeping with the strengths and weaknesses of the systems ideas. In these courses the problem are all open-ended. The students are asked to focus on the processes they are following and the assumptions they are making, as opposed to on their final result. Finally, the students have the opportunity to choose complex topics that lie outside the traditional boundaries of engineering. Examples of recent workshop topics include the quality of life of Saharan women, living machines, and economic forecasting. Where possible the students are encouraged to work in project teams. In these instances the teaching assistants spend some time with the groups discussing how the various perspectives within the group can be brought together.

RESULTS

Based on anecdotal evidence the Systems Design Engineering curriculum is succeeding in communicating the basic systems concepts. This evidence comes primarily from the perceptions of the teaching faculty and assistants. There are no formal measurements of this success for the simple reason that such measurements do not exist for any topic. While the class averages and failure rates of the systems-specific courses are comparable to those of the other courses, such comparisons are easily critiqued.

The Systems Design programme has the highest entrance average at the University of Waterloo. Its cooperative placement rate is consistently among the highest of the engineering programmes. At provincial and national engineering competitions the Department has won more awards than any other programme and than many other institutions. Many of these awards were for projects that grew out of systems studies. Based on these measurements the merging of systems concepts with engineering has been a success.

CHALLENGES AND OPPORTUNITIES

The most significant challenge faced by the Department in delivering systems content has been a lack of trained personnel and supporting materials. The relative youth of the systems field, especially in the engineering context, makes it difficult to find engineers with the relevant training and expertise. The engineering accreditation criteria promote the hiring of engineers over non-engineers. This favoured treatment has led to a shortage of appropriately trained faculty within the Department. The relative youth of the field also makes it difficult to find textbooks, exemplars, and other teaching materials.

As an interdisciplinary department Systems Design has had difficulty attracting funding and explaining itself to others. Students are continually asked in employment interviews “What exactly is Systems Design Engineering?” while faculty members apply for funding under the auspices of traditional disciplines. Although NSERC, the major Canadian research funding agency, attempts to promote interdisciplinary research, its structure is not conducive to supporting such work.

There are however causes for optimism. Selected systems concepts are being introduced into secondary school curricula. The terms ‘interdisciplinary’ and ‘transdisciplinary’ are appearing more and more in reports from engineering associations, business groups, and government. Most promising is the recent formation of the environmental research and education directorate by the National Science Foundation (NSF) in the United States, and in particular, its Biocomplexity programme This directorate's mandate is novel within the NSF for three reasons. First, it is explicitly interdisciplinary in nature. Second, it focuses explicitly on the issue of complexity. Third, part of its primary mandate is to promote education. The Department of Systems Design Engineering is one of the few existing academic programmes whose core mandate is to address the same issues as this new NSF initiative. The potential for the Systems Design Engineering to develop, and for its ideas to spread, is greater than ever before.

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