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# Developing a Systems Thinking Integration Approach for Robust Learning in Undergraduate Engineering Courses

**Dr. Federica Robinson-Bryant, Embry-Riddle Aeronautical University- Worldwide**

Dr. Federica Robinson-Bryant is an Assistant Professor at Embry-Riddle Aeronautical University- Worldwide. She is the Program Chair for the Master of Systems Engineering program and a member of the Dept. of Engineering and Technology.

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## Abstract

Traditional engineering programs tend to foster discipline autonomy and teach domain-specific technical matter despite diminishing boundaries among the engineering disciplines. Little-to-no coursework aims to help students understand the holistic implications of design decisions and inherent limitations of discipline views over the lifecycle of systems. Promoting the learning of meta-competencies rather than competency development is suggested to better prepare engineering students for the ill-structured problems they will likely face after graduation. Researchers have raised the question of whether the objective of education is one of imparting highly specialized domain knowledge or rather learning and making connections across domains. This helps to prepare students to learn new skills as needs emerge, hence the emergence of the notion of 'robust knowledge'. The adaptation of the underlying Knowledge Learning & Instruction Framework yields a novel approach to integrating systems thinking skills in engineering courses, despite conflicting schools of thought of how and when integration should occur.

This work in progress paper describes a systems thinking skills intervention developed for an online, Project Management course for 3rd and 4th year engineering students. The application of a vertical, course thread fosters "deep, connected and coherent" exposure to systems thinking skills. The Conceptual Systems Thinking Integration approach introduced herein not only outlines instructional events, learning events, knowledge features and assessment events that will be applied to facilitate robust learning of systems thinking skills, but also provides a literature-based discussion of the growing importance of developing an orientation towards systems thinking skills for all engineers.


## Background

Significant discourse exists in engineering education in the United States, especially in the preparation of undergraduate students for the dynamic and complex enterprise they will eventually join. Each year, an average of approximately 80,000 undergraduate students graduate from engineering programs [1]. Many of these programs foster discipline autonomy and teach domain-specific technical matter despite diminishing boundaries among the engineering disciplines. Little-to-no coursework aims to help students understand the holistic implications of design decisions and inherent limitations of discipline views over the lifecycle of systems. An impetus for the 'correct answer' to defined problems have precluded the need for truly analyzing problems [2] or managing engineered solutions. Moreover, fragmented and prescriptive learning continues to discount the development of interdisciplinary knowledge and therefore hinders optimal transferability to real-world engineering practice [3].

A preliminary survey disseminated among industry, academia and government participants revealed a unanimous belief that systems thinking (ST) skills is needed by all engineers and that engineers do not possess the desired proficiency in these skills upon graduation from undergraduate programs [4]. This result is supported by commonly cited findings that engineer turnover is partly due to a lack of understanding of the big picture and "boring work" (or a lack of appreciation for engineering functions beyond hands-on, engineering design). A national, Canadian survey showed similar results [5]. The most common reason for engineer turnover (voluntary and involuntary) were related to conflict with the role itself, including the engineer's desire for a career change, job satisfaction and feelings of the role being a poor fit. Accordingly, researchers, educators, industry, government and accreditation bodies all posit the need for systemic and transformative change in engineering education [4], [6], [7], [8] as society continues to demand increasingly complex, interrelated and global systems.

For instance, the organization that accredit engineering programs in the U.S., ABET, has approved changes toward systemic and globally relevant student outcomes effective 2019-2020 review cycle. This need is also evident in its new definition of engineering design [8].

**Integrating ST in Engineering Programs**

The International Council on Systems Engineering (INCOSE) envisions that systems engineering becomes "a part of every engineer's curriculum and systems engineering at the university level [be] grounded in the theoretical foundations that spans the hard sciences, engineering, mathematics, and human and social sciences" [9]. There has been "little penetration of systems engineering instruction into the undergraduate engineering curriculum" [3] although more formalized guidance has been developed for those interested in developing graduate systems engineering programs (GRCSE) [10]. As of 2016, fifteen U.S. institutions had already implemented stand-alone undergraduate SE programs while others have opted to add somewhat insulate systems engineering coursework into existing programs.

A search of the literature suggests that no curriculum framework focusing on developing systems thinking among all engineers exists [11]. Hence, future research efforts must pivot toward approaches to address the needs of a broader range of engineers as suggested in this effort. Figure 1 captures 4 main levels to integrate systems thinking in engineering programs, which supports at least 5 different schools of thought currently found in the literature [4]. Determination of strategy rests on many factors like institutional demographics, program size and modality so "one size fits all" solutions are less likely to prompt truly transformative change across engineering education.

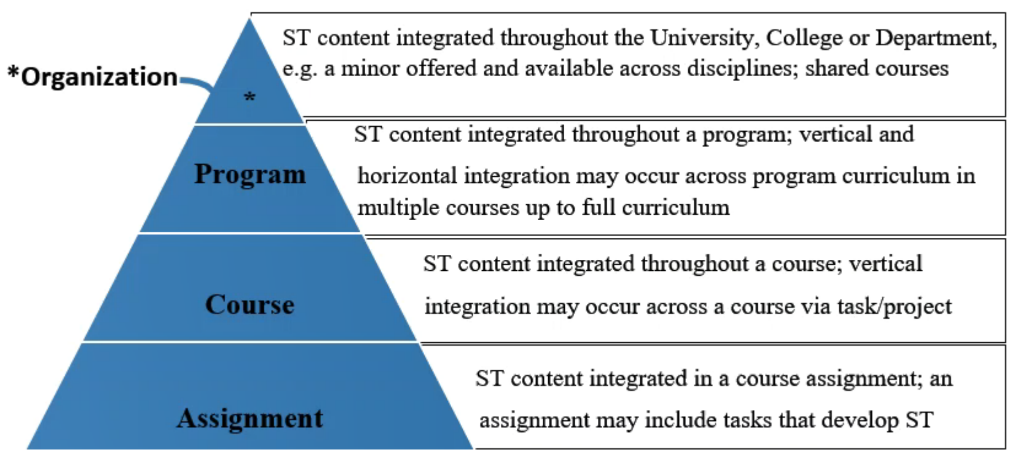


**Figure 1. Levels of ST Integration**

## Project Objective

The goal of this project is to design, develop, implement and evaluate a systems thinking intervention at the Course level that aims to foster the development of systems thinking skills among multi-disciplinary undergraduate engineering students. Current efforts have included the design and development phases and the first implementation is planned for later this year. The project aims to (A) evaluate whether students exhibit a positive change in systems thinking after the systems thinking intervention, (B) assess the validity of the ST instrument adapted to this project and (C) assess the validity and reliability of the grading rubric developed for this intervention. Exploratory analysis will also occur via use of meta-data available in the course management system.

## Phase I: Design- The Conceptual Approach

Systems thinking is a concept that dates back as early as the 1920s and is grounded in theories of holism (attributed by Aristole, coined by J C Smuts), general systems theory, relational thinking, and cybernetics. Many well-known approaches have derived from earlier works [12] but the common manipulation of semantics or the subtle interchange of one or more component causes many disciplines and organizations to create different understandings of systems thinking. This colludes the ability to make substantive progress in the field. Rather than subscribing to one perspective over another, a distillation of existing works synthesize the pluralism and provide a common language for researchers [7]. The resulting set of 14 areas of systems thinking skills combined 20 different models, frameworks and popularized informal references to systems thinking skills to form one skill set termed the Areas of Systems Thinking Skills (ASTS).

**Table 1. Areas of Systems Thinking Skills**

| Areas of Systems Thinking Skills (ASTS) | |
|---|---|
| **ASTS1. Multiple Perspectives**: Various dimensions and points of view based on system life cycles, stakeholders, multiple disciplines, technical and business factors and other non-engineering influences (*e.g. ecological/environmental, marketing, political, organizational, economical, human factors (personal issues, personality styles), etc.)* | **ASTS8. Mental and Formal Models:** Skeptic reception of information and self-consciousness of strengths, weaknesses, behavior and informal and formal boundaries relative to other elements |
| **ASTS2. Different Scales of Abstraction**: Varying levels of understanding of a system and its behavior including its elements, subsystems, assemblies and components, and systems of systems | **ASTS9. System Structure & Boundaries**: Elements and interconnections between elements defining system definition, purpose, context and environment |
| **ASTS3. Interconnections, Intra-relationships and Dependencies:** Linear interactions and constraints between system elements (internal and external system boundaries) at different hierarchical levels | **ASTS10. Conceptual Modeling**: Representation of a system and its composition and relationships in different ways using simplification methods *(e.g. reduction, transformation, abstraction and homogenization)* |
| **ASTS4. Dynamic Behavior**: Variation in system response as a function of its relationships, dependencies, stimulus, people, environment and feedback, including emergent behavior | **ASTS11. Prospection & Prediction:** Anticipate impact and implications of changes over the lifecycle of the system |
| **ASTS5. Stock, Flow and Delay:** Physical, financial, intellectual and/or human resources in a system, changes in resources and any lag in the impact of those changes | **ASTS12. Hypothetical & Inferential Consideration**: Inductive and deductive inference from multiple disciplines into one's decision making process |
| **ASTS6. Feedback**: Negative and positive cause and effect loops among interconnections and its impact on system behavior | **ASTS13. Paradoxical & Ambiguity Tolerance**: Capacity to deal with ambiguity, uncertainty and complexity |
| **ASTS7. Non-Linear Relationships:** Complex and non-linear interactions and constraints between system elements (internal and external system boundaries) | **ASTS14: Creativity:** Ability to develop and improve ideas, alternatives and interpretations for some purpose across the system lifecycle |

Moreover, standardized and widely accepted approaches to assessing one's systems thinking ability has proven to be unavailable. Several ST measurement scales are known including Moti Frank's Capacity for Engineering Systems Thinking [13], Systems Thinking Scale of Davis and Stroink [14], Systems Thinking Scale (STS) [15], a ST survey [3], the Systems Thinking Orientation Assessment Framework [16] and an alternative systems thinking scale [17]. The maturity of STS (as measured by diversity of past applications and the consistency of its results) deemed STS as the more appropriate scale for the present project.

**Metacognition**

Metacognition is defined as an individual's knowledge about cognitive processes and the application of that knowledge for controlling those cognitive processes [12], [18]. It is often confused with cognitive skills (the skills needed to perform a task). Some disagreement among researchers exist including whether self-regulated learning is separate from metacognitive knowledge (of persons, tasks and strategies) and metacognitive regulation (planning, monitoring, controlling and evaluating or similar variations) [18]. Yet, self-regulated learning ventures into *how* students become masters of their own learning.

Metacognition show stark parallels to areas of systems thinking skills, including the notions of recognizing inconsistencies and conclusions, identifying constraints and switching from one representation to another. Recent studies have begun to explore the utility and transferability of metacognition in engineering students [18] but questions of whether metacognitive strategies can foster the development of systems thinking remains a valid one. A widely used and validated instrument, the Metacognitive Awareness Inventory [16], has been adapted to a custom, interactive medium to investigate this question during this project.

**Robust Learning**

Robust Learning refers to knowledge that can transfer to other situations and that is retained long-term [19], [20]. It was developed based on the Knowledge-Learning-Instruction Framework (KLI) developed by [21] and captures the relationships between observable instructional and assessment events and inferred events and knowledge. KLI was "designed to integrate instruction, knowledge structures, and cognitive processes as core features of a unified, domain-independent theoretical framework [21]."

Moreover, researchers in this area [19] raise the question of whether the objective of education is one of imparting highly specialized domain knowledge or rather learning and making connections across domains to prepare students to learn new skills as needs emerge. Promoting the learning of meta-competencies rather than the more traditional approach of competency development is suggested to better prepare students for the ill-structured problems they will likely face after graduation.

Figure 2 captures an adaption of the KLI Framework and the Framework of Robust Learning for this project. It shows specific features of robust knowledge (deep, connected and coherent learning) and has proven generic [19] and adaptive to various assessment events and instructional events.

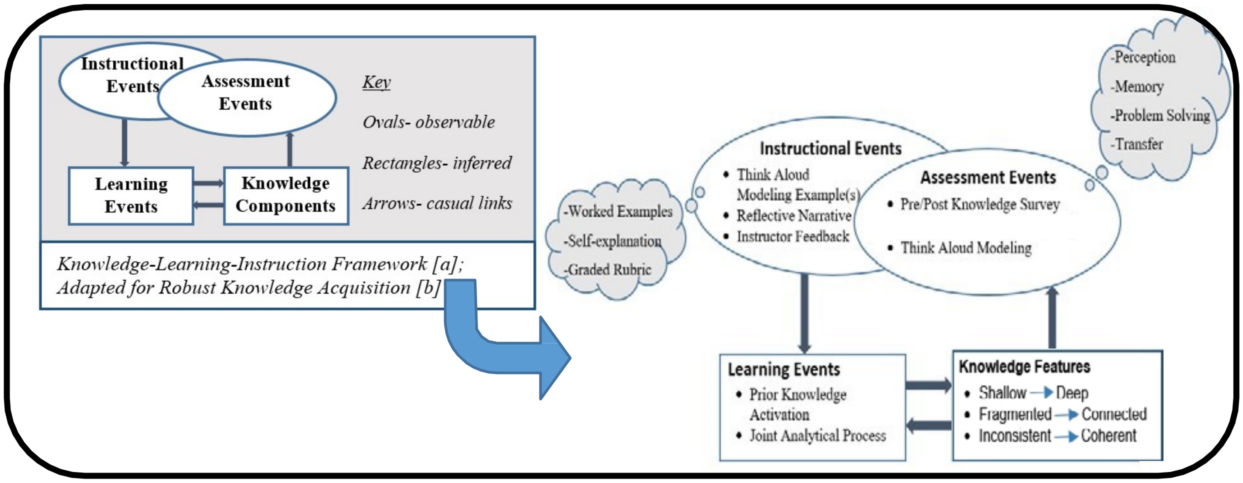


**Figure 2. Conceptual Systems Thinking Integration Approach**

**Phase II- Develop- Creating the Intervention for an Online Context**

The online course is a 9 week, 9 module intensive course in Project Management. It was a new course development and provided the opportunity to systematically construct the intervention and its dissemination strategy. The chosen events support the conceptual approach in Figure 2 and are described below.

<u>Pre/Post Knowledge Surveys</u>

*Description:* Pre- and Post- surveys featuring a combination of Likert scale and binary response items will be used to self-assess individual familiarity, interest, knowledge, or experience with systems thinking and metacognition.

*Dissemination:* The Metacognitive Awareness Inventory (Figure 3) and the Systems Thinking Scale (Figure 4) will be distributed as two separate instruments in Modules 1 and 9 of the course and are delivered using interactive tools. Students have 1 week to complete both instruments and electronically submit.


**Figure 3. Metacognitive Awareness Inventory Assessment Excerpt**

**Systems Thinking Assessment**

**Instructions:** Please read each of the statements and select the option that indicates the frequenc
with the statement. To clear the form, click the **RESET FORM** button at the bottom of the page.

**Name:**                          **Date:**

| When I Want to Make an Improvement ... | Never | Seldom | Some of the Time | Often | Most of the Time |
|---|---|---|---|---|---|
| 1. I seek everyone's view of the situation. | ○ | ○ | ○ | ○ | ○ |
| 2. I look beyond a specific event to determine the cause of the problem. | ○ | ○ | ○ | ○ | ○ |
| 3. I think understanding how the chain of events occurs is critical. | ○ | ○ | ○ | ○ | ○ |
| 4. I include people in my work unit to find a solution. | ○ | ○ | ○ | ○ | ○ |
| 5. I think recurring patterns are more important than any one specific event. | ○ | ○ | ○ | ○ | ○ |
| 6. I think of the problem at hand as a series of connected issues. | ○ | ○ | ○ | ○ | ○ |
| 7. I consider the cause and effect that is occurring in a situation. | ○ | ○ | ○ | ○ | ○ |
| 8. I consider the relationship among coworkers in the work unit. | ○ | ○ | ○ | ○ | ○ |
| 9. I think that systems are constantly changing. | ○ | ○ | ○ | ○ | ○ |
| 10. I propose solutions that affect the work environment, not specific individuals. | ○ | ○ | ○ | ○ | ○ |
| 11. I keep in mind that proposed changes can affect the whole system. | ○ | ○ | ○ | ○ | ○ |
| 12. I think more than one or two people are needed to have success. | ○ | ○ | ○ | ○ | ○ |
| 13. I keep the mission and purpose of the organization in mind. | ○ | ○ | ○ | ○ | ○ |
| 14. I think small changes can produce important results. | ○ | ○ | ○ | ○ | ○ |
| 15. I consider how multiple changes affect each other. | ○ | ○ | ○ | ○ | ○ |

**Figure 4. Systems Thinking Scale Adaption in Online Course, excerpt**

*Assessment:* The initial and final assessments will be used to evaluate changes in metacognitive awareness and systems thinking and any relationship among the two.

*Value Proposition:* Students will connect prior knowledge with the learning objectives, be able to consciously adjust/adapt learning processes between assessments and understand the impact of their processes on achieving a robust learning experience. Resulting data will characterize individual change after ST intervention and provide formative and summative results that support comparative analyses between the two constructs.

## Think-Aloud Modeling

*Description:* The instructor will provide Think Aloud examples using various mediums (e.g. text, video, animations and audio) that demonstrate the cognitive processes of systems thinking (see Figure 5). Then, on multiple occasions throughout the course students will use a medium of their choice to assume the role of a specified stakeholder (e.g. customer, engineer, systems architect, regulatory body, etc.) and query how a specific area of systems thinking skills manifests in project tasks (see Figure 6). Each student will be required to demonstrate this individual modeling prior to the collaborative task. In the collaborative task (*or a discussion board*), students will extend each other's thinking by asking questions, posing alternative reasoning and offering constructive feedback.

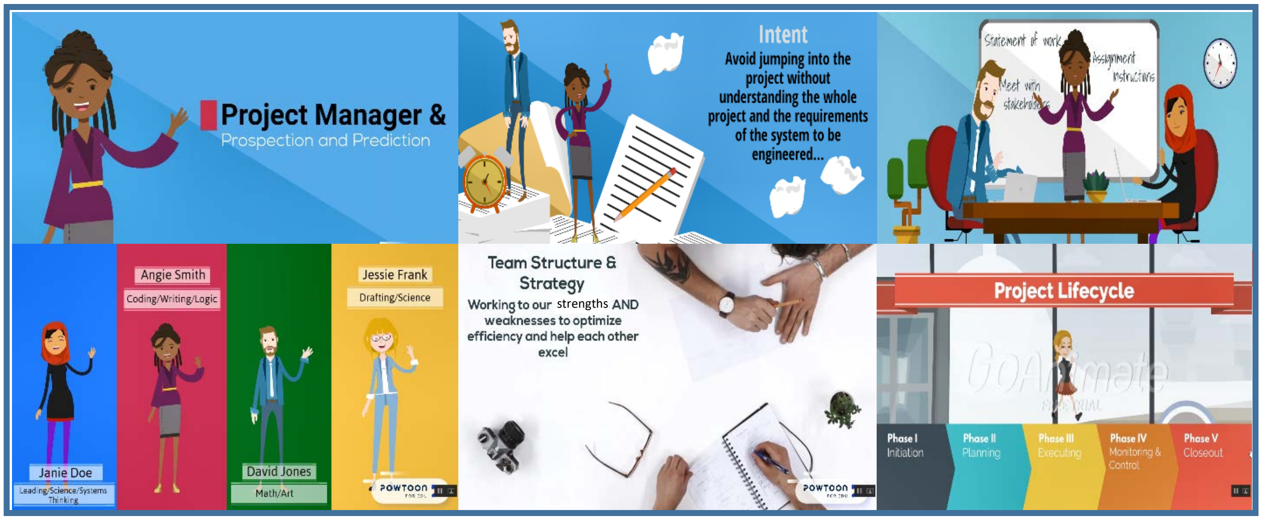


**Figure 5. Think Aloud Example (2 minute animation)**

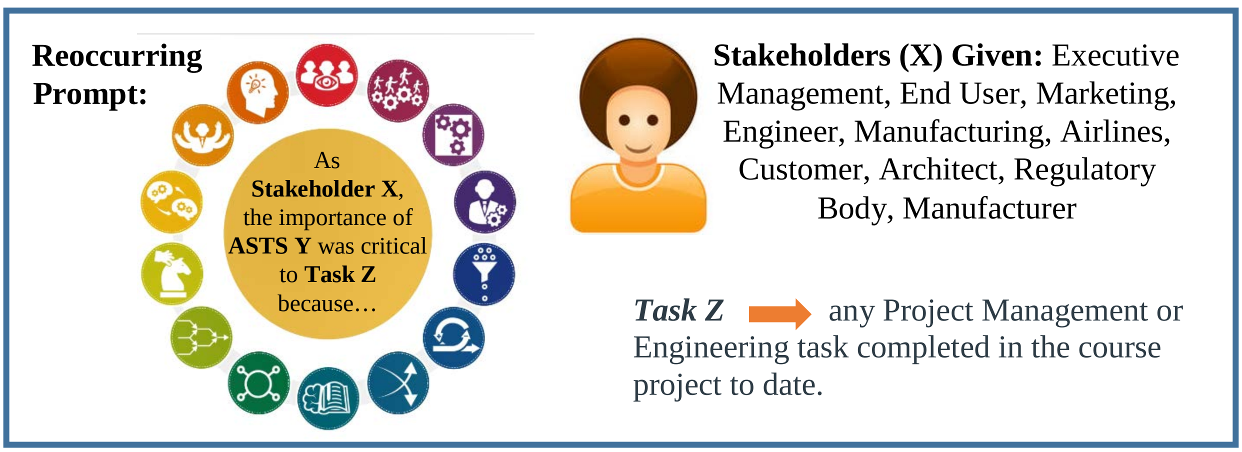


**Figure 6. Example Student Think Aloud Prompt**

*Dissemination:* All activities will occur within the online course management system using the discussion board for public posts. The students and instructor will have access to this forum.

*Assessment:* The rubric is structured to explicitly assess the 14 areas of systems thinking skills [7] and several features of robust learning [19]. The graded feedback will be provided to each student at the end of each instance of the instructional event.

*Value Proposition:* Deliberate and critical cognitive processes across the areas of systems thinking skills will highlight systems thinking (or lack thereof) per area of systems thinking and provide students an opportunity to adjust their own processes relevant to a targeted subset of the systems thinking skills. Identification of patterns and correlations of participant performance on this task will allow convergent validity testing between the results and the systems thinking construct.

Reflective Narrative

*Description:* Students will provide open-ended reflections after each Think Aloud activity and one report on systems thinking and its implications on project management and engineered systems at the end of the course.

A. The open-ended reflections focus on how the student engaged and learned in the course. It encourages students to recognize positive, negative and neutral aspects of the task(s).

B. The report challenges students to determine whether they perceive a benefit of systems thinking in engineering and must support their position. Any individual adjustments made between the pre- and post- knowledge survey is expected in the student's report.

*Dissemination:* After each instance of the Think Aloud activity, students must provide reflections on learning during that experience. All activities will occur within the online course management system using a blogging feature for personal reflections. The instructor will have access to this forum but will not intervene in the personal reflection process unless warranted.

*Assessment:* Students will be graded per a simple rubric that focuses on completion of the activity rather than the accuracy or depth of reflection. Inductive coding methods will be used to detect patterns and themes in student reflections.

*Value Proposition:* Students will be conscious of their cognitive processes and better oriented towards systems thinking through reflective inquiry. These events foster continuous course and project improvement and provides many opportunities for clarifications and recommendations to optimize the student's learning experience.

**Next Steps… Phases III & IV**

The systems thinking intervention described in this paper is embedded into an online course template and is pending implementation. The first cohort of students will take the course later this year and any necessary adjustments will be made to the intervention design and/or delivery strategies. This paper serves as an introduction to that intervention and its theoretical grounding. Participants will gain a first-hand look at (A) how this intervention is structured for the online setting, (B) example artifacts including instructor's Think Aloud examples, the MAI and Systems Thinking Scale assessments and the systems thinking rubric and (C) discuss ways the intervention could be adapted in alternative delivery modes.

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