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Elsevier

Towhidnejad, Massood, et al. "Enabling systems engineering program outcomes via Systems Engineering Body of Knowledge." Procedia Computer Science 16 (2013): 983-989.
http://hdl.handle.net/10945/59884

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Enabling Systems Engineering Program Outcomes via Systems Engineering Body of Knowledge

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Abstract

With the ever-increasing complexity of systems, it is important to properly educate the upcoming systems engineering workforce. The Graduate Reference Curriculum for Systems Engineering (GRCSE) provides guidelines for graduate program degrees in systems engineering. GRCSE establishes a baseline set of entrance expectations, objectives, outcomes and content for any graduate degree in systems engineering. GRCSE recognizes that each university needs to meet the needs of their constituents, and for this purpose, GRCSE only defines 50\% of the program content, and leaves the other 50\% to be defined by individual universities to satisfy the needs of their stakeholders. The purpose of this paper is to introduce GRCSE’s outcomes, and how those outcomes can be attained through the program content.

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Keywords: Systems Engineering; Graduate Program; Program Outcomes; Competencies

1. Introduction

With the ever-increasing complexity of systems, it is important to properly educate the upcoming systems engineering workforce. The Graduate Reference Curriculum for Systems Engineering (GRCSE) fills a gap in the international systems engineering community by providing guidance to the range of stakeholders interested in graduate level systems engineering education. GRCSE (Pyster, 2012; Towhidnejad, 2013) assists these stakeholders in making judgments associated with the development, maintenance, and selection of graduate level Systems Engineering Masters programs.

GRCSE is organized into nine chapters and seven appendices; the following presents a brief description of each chapter.

- Chapter 1 provides an overview of the GRCSE document, including a discussion of multiple paths which one could pursue as a graduate degree.
Chapter 2 describes the objectives students should attain three to five years after graduation.

Chapter 3 states the outcomes that a student is expected to achieve immediately upon graduation.

Chapter 4 details the background students are expected to possess before entering a master’s program.

Chapter 5 presents curriculum architecture for structuring a SE program and a common mechanism for communicating the components of an institution’s SE graduate level curriculum. The GRCSE architecture shows the relationships and overlap between the Core Body of Knowledge (CorBoK), domain or program-specific topics, capstone experiences, and levelling courses.

Chapter 6 describes the CorBoK, which includes both the foundation (topics which should be learned by all students) and the concentrations (topics which should be covered by students focusing on a specific SE role). The CorBoK is intended to cover no more than 50% of the total knowledge conveyed in a graduate program. Making the core knowledge 50% of the program instils critical commonality among programs. Employers will have more information regarding what students graduating with a master’s program have learned and are capable of doing. Restricting the CorBoK to no more than 50% encourages significant variation among programs while simultaneously building on the common foundation. This ensures an opportunity for the student to develop a deeper knowledge in topics of particular interest, such as requirements elicitation and analysis or system architecture.

Chapter 7 includes guidance on implementation, focusing on using GRCSE as a tool for curriculum development and revision. It includes considerations for tailoring GRCSE recommendations to fit a program’s specific needs in terms of stakeholder requirements and environmental constraints. For example, to align with the GRCSE recommendations, a program should enable its students to achieve all thirteen outcomes listed in Chapter 3, but that program could also add several outcomes that are specific to that program’s clientele, faculty interests, and other relevant factors.

Chapter 8 provides guidance for developing assessment rubrics to ensure that graduate programs achieve their intended outcomes. This chapter is built on the general discussion of the relationship of student learning and assessment in Appendix E.

Chapter 9 explains the intended evolution and long-term support of GRCSE.

Amongst its many contributions, GRCSE contains 1) a description of the outcomes expected of Masters programs in systems engineering and 2) a description of the levels of achievement, expressed in terms of the cognitive domain of Bloom’s taxonomy of educational outcomes, expected of graduates or program in specified subject matter. This subject matter is referred to as the Core Body of Knowledge (CorBoK) and is outlined and described in the Systems Engineering Body of Knowledge (SEBoK) (Pyster, 2012) developed as part of the Body of Knowledge and Curriculum for the Advancement of Systems Engineering (BKCASE) project.

In the process of developing GRCSE, the authors decided to include a mapping of the CorBoK content, referred to as topic areas, to the achievement of outcomes. The result of this mapping process is provided in a GRCSE appendix. However, in the process of developing the table describing the relationship of the topics to be learned about and the outcomes expected of students, patterns were identified. One pattern observed was that a number of outcomes shared the same set of topics as the content that would support their development. This observation has in turn been exploited in the main body of GRCSE to organize the original 13 outcomes into four primary groups. This grouping simplifies the expression of the outcomes, to assist readers, but also suggests an underlying structure to the relationship of the topic areas to systems engineering education.
2. Background

2.1. Outcomes

In the GRCSE context, outcomes refer to what students are able to achieve during an educational program up to the time at which they graduate, having successfully completed the program. The primary factors impacting the achievement of outcomes are the content and manner of teaching of the program, the broader institutional context in which students study, and the abilities that students have at the time that they enter the program. The relationship of entry requirements to a program and the achievement of students during the program are based on the assumptions that the teachers in the program can make about the students prior knowledge as they proceed with the activity of teaching. Each student comes to a program with some range of abilities and knowledge. Using the program entry criteria to constrain the range of student knowledge at the time of entry to include the defined range is very useful because it enables teachers to build upon that knowledge. In contrast, a less constrained entrance requirement would allow more students to enter the program but would allow teachers much less foundation for assuming background knowledge, thereby making it more difficult to advance the program graduates to the same outcome ability.

It is intuitively clear that the outcome of an education program will be dependent on the combination of what is taught and the methods of teaching and assessment which are used to teach that content.

The university context significantly impacts the learning that students achieve because of the range of experiences that this context enables students to have during the time of their study. The university context is something within the authority of the University to control, although it is probably outside the authority of the department that offers the program to control. The context will include such factors as the resources and facilities available to students and the general campus culture, which provides opportunities for students to learn a variety of things that may be of professional value but not specifically the subject matter of their particular program.

GRCSE defines 13 outcomes organized into four groups, as shown in Table 1.

2.2. Core Body of Knowledge (CorBoK)

The Core Body of Knowledge (CorBoK) presented in GRCSE is closely connected to the outline of the SEBoK product of the BKCASE project. The topics about which GRCSE expects students to learn are the knowledge areas and topics presented in the contents list of the SEBoK. The SEBoK contains an article discussing each of the topics included in CorBoK, which can be used to provide information about what is meant by each of the topics included in CorBoK and also to provide expanded content and references which will be useful to educators developing teaching materials.

The CorBoK tables define the minimum level of attainment in the cognitive domain of Bloom’s taxonomy of educational outcomes that students should achieve during their enrollment in a Masters program in systems engineering for each topic area. Bloom’s taxonomy and the rationale for using it in GRCSE are discussed in an appendix of GRCSE. The appendix includes a discussion of the interpretation of the levels defined in Bloom’s taxonomy tailored to the subject matter of systems engineering and tables also suggest types of assessment tasks that could be used to test student attainment for each of the levels. This information is included both to assist curriculum designers to develop appropriate assessment methods to determine that students have attained the kind of learning that is intended and to show to stakeholders the capabilities that the GRCSE authors have associated with the names of the levels in Bloom’s taxonomy. The authors believe that this is an important contribution to clearly communicating the intention of GRCSE.

2.3. Systems Engineering Roles and Required Competencies

It is generally understood that the role a person needs to perform drives the types of competencies that person needs. The systems engineering competency models typically include a set of competencies, and varying levels of proficiency in those competencies, but do not address specific systems engineering based roles such as systems integrator, systems tester, systems requirements manager, systems developer, or systems engineering manager, which are associated with those competencies. A comparison of current systems engineering competency models
demonstrates some consistency in the core competency areas of systems engineering, specifically systems engineering implementation activities across the life cycle. However, the models tend to vary widely in the selection of the key broad based competencies such as effective communications, systems thinking, project management, coaching and mentoring, problem solving, ethics, and leadership (Ferris, 2010; Squires, 2011; Kasser, et. al. 2012). A focus on the role of the systems engineer in the organization can help bridge the gaps between systems engineering competency models currently being leveraged across industry, government, and academia and the needs of employer organizations. To this end, the National Defense Industrial Association (NDIA), Systems Engineering Division (SED)’s Education and Training (E&T) Committee is currently considering the incorporation of specific roles in the collaborative development of a common systems engineering competency framework with the International Council on Systems Engineering (INCOSE) Competency Working Group. The outcome of this work will inform the design of education programs by guiding the details of the descriptions of objectives and outcomes, and thus the teaching content and methods required to achieve the outcomes and objectives specified.

Table 1. GRCSE outcomes for a master’s program in systems engineering

| Outcome Area      | Outcome Description                                                                                                                                 |
|-------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| SE Concepts       | **Foundation** – Achieve designated Bloom’s levels of attainment for each topic contained within the CorBoK foundation.                           |
|                   | **Concentration** – Achieve designated Bloom’s levels of attainment for each topic contained within one of the CorBoK concentrations, as appropriate for the type of master’s program of for an individual student’s interest. |
|                   | **Topic depth** – Achieve a Bloom’s synthesis level of attainment for at least one topic from the CorBoK (either foundation or concentration).           |
| SE Role           | **Application Domain** – Demonstrate the ability to perform SE activities in one application domain, such as defense, aerospace, finance, medical, transportation, or telecommunications. |
|                   | **Specialty** – The Application of SE principles to address a specialty such as security, agility, or affordability, or such as safety-critical or embedded systems. |
|                   | **Related Disciplines** – Comprehend the relationships between SE and other disciplines, such as project management, human factors, and other engineering fields as discussed in the SEBoK and be able to articulate the value proposition of these disciplines for SE. |
|                   | **Software in Systems** – Demonstrate an understanding and appreciation of the level of software engineering necessary to develop current and future products, services, and enterprise systems. |
| SE Practice       | **Requirement Reconciliation** – Be able to reconcile conflicting requirements, finding acceptable compromises within limitations of cost, time, knowledge, risk, existing systems, and organizations. |
|                   | **Problem/Solution Evaluation** – Be able to evaluate alternative system solution strategies, including how well different solutions relate to the identified problem, and express relevant criteria to ensure solutions are selected against a holistic systems perspective. |
|                   | **Realism** – Comprehend and appreciate the challenges of applying SE to realistic problems throughout the system life cycle.                           |
| SE Professionalism| **Professional Development** – Be able to learn new models, techniques, and technologies as they emerge, and appreciate the necessity of such continuing professional development. |
|                   | **Teamwork** – Perform as an effective member of a multi-disciplinary team, effectively communicate both orally and in writing, and lead in one area of system development, such as project management, requirements analysis, architecture, construction, or quality assurance, and display leadership capabilities within the team. |
|                   | **Ethics** – Demonstrate knowledge of professional ethics and of the application of professional ethics in decision-making and SE practice.                |

3. Cross Mapping Outcomes and the CorBoK

The appendices of GRCSE include a table showing the mapping between the outcomes of systems engineering programs as recommended by GRCSE and the topics in the CorBoK, which are closely associated with the development of each of the outcomes; this table is shown in Table 2. The table shows strong medium and weak linkage between CorBoK topics and outcomes.
Table 2. Notional mapping of outcomes to Knowledge Areas in the CorBoK of GRCSE. ("M" indicates medium and “S” strong linkage.)

| Knowledge Area | SE Concepts | SE Role | SE Practice | SE Professionalism |
|----------------|-------------|---------|-------------|--------------------|
| **Outcome**    |             |         |             |                    |
| **Knowledge Area** | Foundation | Concentration | Topic Depth | Domain | Application | Specialty | Related disciplines | Software in systems | Requirement reconciliation | Evaluation | Problem/solution | Realism | Professional development | Teamwork | Ethics |
| **Part 2**     |             |         |             |                    |
| System fundamentals | M/S | M/S | M/S | M | M | M | M | M | M |
| System science | M/S | M/S | M/S | M | M | M | M | M | M |
| System thinking | M/S | M/S | M/S | M | M | M | M | M | M |
| Representing Systems with Models | M/S | M/S | M/S | S | S | S | M | S | S |
| Systems Approach Applied to Engineering | M/S | M/S | M/S | M | M | S | S | M | M |
| **Part 3**     |             |         |             |                    |
| Life Cycle Models | M/S | M/S | M/S | S | S | S | S | S | S |
| Concept Definition | M/S | M/S | M/S | M | M | M | S | S | S |
| System Definition | M/S | M/S | M/S | M | M | M | M | M | M |
| System Realization | M/S | M/S | M/S | S | S | M | S | S | S | M |
| System Deployment and Use | M/S | M/S | M/S | M | S | M | M | S | S | M | M |
| SE Management | M/S | M/S | M/S | M | M | M | M | M | M | S | M |
| Product and Service Life Management | M/S | M/S | M/S | M | M | M | M | M | M | M | M |
| SE Standards | M/S | M/S | M/S | S | S | S | M | M | M | S |
| **Part 4**     |             |         |             |                    |
| Product SE | M/S | M/S | M/S | M | M | M | M | M | M | M | M |
| Service SE | M/S | M/S | M/S | M | M | M | M | M | M | M | M |
| Enterprise SE | M/S | M/S | M/S | M | M | M | M | M | M | M | M |
| Systems of Systems (SoS) | M/S | M/S | M/S | M | M | M | M | M | M | M | M |
| **Part 5**     |             |         |             |                    |
| Enabling Businesses and Enterprises to Perform SE | M/S | M/S | M/S | M | M | S | S |
| Enabling Teams to Perform SE | M/S | M/S | M/S | S | M | S | M | S | S | S |
| Enabling Individuals to Perform SE | M/S | M/S | M/S | S | M | S | M | S | S | S |
| **Part 6**     |             |         |             |                    |
| SE and Software Engineering | M/S | M/S | M/S | M | S | S | S | M | M | M | M |
| SE and Project Management | M/S | M/S | M/S | M | S | M | M | M | S |
| SE and Industrial Engineering | M/S | M/S | M/S | M | S | S | M | M | M | M | M |
| SE and Procurement/Acquisition | M/S | M/S | M/S | M | S | S | M | M | M | M | M |
| SE and Specialty Engineering | M/S | M/S | M/S | M | S | S | M | M | M | M | M |
When the table was developed, the GRCSE authors recognized patterns in the linkages between topics and outcomes that resulted in grouping sets of outcomes that have identical or similar linkages to the topics. The grouping was accomplished through the use of four categories:

1. SE Concepts
2. SE Role
3. SE Practice
4. SE Professionalism

This organization of sets of outcomes was then iteratively used to organize the presentation of the table and to arrange the order of presentation of the outcomes. Organizing the outcomes into four groups rather than 13, enables users to more profoundly engage with the set of outcomes provided, and because the grouping of outcomes is based on the observed similarity of the topics with which they are associated, it is a natural rather than forced or arbitrary grouping of the subject material. The grouping also addresses the concerns of early GRCSE reviewers that 13 outcomes was simply too many to address all at once, now the focus can be on three to four outcomes at a time as each of the four outcome areas are addressed.

The grouping further supports a competency framework for systems engineers. This framework would provide guidance based on the systems engineering role being addressed, for a foundational set of systems engineering competencies covering the broad set of topic areas in the CorBoK; a set of systems implementation specific competencies; and a set of broad professional competencies.

4. Future Research

One future area of research that is clearly evident from this research is the need to link the systems engineering reference curriculum developed to a common systems engineering competencies framework. This effort could build on previous works on mapping specific systems engineering curriculums to specific competency models (Chyung, Stepich, and Cox, 2006; Goncalves, 2010; Squires, Larson, and Sauser, 2010; Squires and Cloutier, 2010). The value of such work would be to strengthen the tools available to key stakeholders in their use of GRCSE. Linking GRCSE and competency frameworks is useful because many organizations employing systems engineers use a competency framework, whether one that they have developed themselves or one may have obtained from an external source, in order to organize their recognition and work assignment of systems engineers.

A second area of future research is to compare GRCSE with a variety of Masters programs in systems engineering offered around the world. This will enable understanding of how completely existing programs reflect the GRCSE recommendations and the nature of any differences between GRCSE and individual programs or the program is viewed in aggregate. In principle, if the differences between GRCSE and each program are different then the differences would reflect the individual choices which GRCSE permits as part of the 50% of the University specific material. If the differences between the programs and GRCSE are very similar the result is that the future maintenance of GRCSE should review the differences as an input to the revision cycles.

5. Conclusions

In this paper we have described the relationship of two parts of the GRCSE document; the CorBoK and the program outcomes. In itself the relationship was interesting to obtain but once obtained provided some helpful insight into the relationship of particular topics in systems engineering and the competencies of systems engineering reflected through the statement of the program outcomes.

The impact of identifying groups of topics which are associated with groups of educational outcomes for systems engineering programs is that the arrangement can be used to design educational curriculum which is efficient in the sense that it enables linkage of groups of topics into a structure which would appear to provide a natural course structure.
Acknowledgements

The authors of this paper are contributing authors to GRCSE. The authors of this paper thank the remaining contributing authors to GRCSE for their work in developing GRCSE, and the ideas underlying this paper: Rick Adcock, James Anthony, John Brackett, JJ Ekstrom, Richard Freeman, Thomas Hilburn, Nicole Hutchison, Peter Jackson, Naohiko Kohtake, Steven Mitchell, David Olwell, Art Pyster, Seiko Shirasaka, Guilherme Travassos and Mary VanLeer.

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