Developing the Requirements for Introductory Courseware for Systems Engineering

Joseph E. Kasser DSc, CEng, CM
Systems Engineering and Evaluation Centre
University of South Australia
Mawson Lakes, SA. 5095
Joseph.kasser@incose.org

Abstract. This paper sets out to determine the scope for the requirements for the content of introductory courseware in systems engineering and the requirements for the pedagogy (process) to make learning effective. Beginning by stating the apparent current confusion within the discipline, the paper asks and answers the following three questions.

1. What is systems engineering?
2. What do systems engineers do in the workplace?
3. What is a systems engineer?

In providing answers to the questions, the paper scopes the requirements based on the skills and knowledge needed by systems engineers as well as factors that enhance teaching and learning, and concludes that a new set of introductory courseware is needed to fill the gap in the curriculum of existing courses.

OBSERVATION AND HYPOTHESIS

After many years of experience as a practitioner and educator, I have observed that Systems engineering is, in general, often poorly practiced. My hypothesis is that one reason for this situation is that it is poorly taught due to the lack of good teaching materials and the lack of awareness of factors that expedite learning.

The literature on systems engineering education and curriculum design (e.g. (Asbjornsen and Hamann, 2000; van Peppen and van der Ploeg, 2000; Sage, 2000; Brown and Scherer, 2000; Thissen, 1997; Jain and Verma, 2007)) focuses on the content to be taught, and tends to ignore pedagogical issues. Although there are a number of books on systems engineering, including (Kasser, 1995), they are based on the author's experience, written from a single perspective (Thissen, 1997) and are designed for practicing systems engineers, and consequently not optimal for teaching at the introductory level. Thus, they are generally not accompanied by appropriate courseware.

PROCESS FOR CREATING COURSEWARE

The ideal instructor for these courses is an accomplished practitioner working in the field (day job) and teaching part-time. However, while recruiting these practitioners in the Graduate School of Management and Technology at University of Maryland University College (UMUC), I found that these people do not have the time to prepare course materials. Thus, a set of courseware and a textbook designed for the teaching of introductory systems engineering should improve the situation. To develop the requirements for this introductory courseware, we need to identify what is currently being taught, and ask, "are we teaching the students what they need to know?' and ask ourselves, "Are they learning what we teach? (and, if not, why not?)

Designing a curriculum is an example of systems engineering of both the product and the process. As (van Peppen and van der Ploeg, 2000) wrote "*typically, an educational program is carefully designed, giving attention to the individual elements of the curriculum, the learning environment, and their interdependencies. A curriculum design (a specific sequence of knowledge-base and skill-building courses) specifies the criteria for course design (a specific combination of learning objectives, course materials, teaching methods, and tests), as well as the staffing of teaching faculty, course scheduling, and teaching facilities*." This paper describes a systems engineering approach to designing introductory courseware (the system). The process for creating this courseware shown in Figure 1 is based on (Kasser, et al., 2004). The steps are:

1. Develop a better understanding of the need.
2. Document a set of requirements for the knowledge courseware and book.
3. Develop a prototype set of the materials.
4. Test the prototype in short courses and in parts of regular courses in several institutions.
5. Revise the prototype materials into the final version.
6. Submit the final version to an appropriate publisher.

The scope of this paper is limited to the first step of the process, namely discussing the requirements for the subject matter of the courseware based on Customer Needs, the Body of Knowledge, and Benchmarks or current offerings by tertiary institutions, together with an introduction to the requirements based on factors that make learning effective based on cognitive psychology principles.

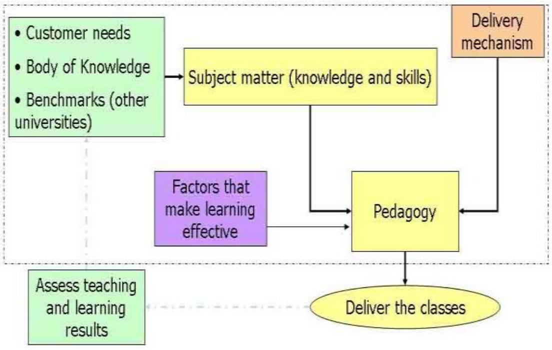

Figure 1 Process for crafting a degree

THE CUSTOMER NEEDS

The customer needs aspect was addressed in INCOSE UK's set of competencies for systems engineering to enable both employers and employees to define the required systems engineering skills needed from both individuals and teams (Hudson, 2006). I hope INCOSE UK won't mind if it is used by an educator to help define the requirements for what has to be taught to prospective systems engineers.

BENCHMARKS

A literature search produced a number of benchmarking studies e.g. (Brown and Scherer, 2000). In addition, the International Council on Systems Engineering (INCOSE) Academic Council has recently performed a review of system engineering programs and curricula (Jain and Verma, 2007). Thus, the contents of this report and the benchmarking studies can provide the initial requirements based on current offerings.

THE BODY OF KNOWLEDGE

In order to develop the knowledge and skill requirements we need the answers to the following questions:

1. What is systems engineering?
2. What do systems engineers do in the workplace?
3. What is a systems engineer?

Consider each of them in turn:

WHAT IS SYSTEMS ENGINEERING?

If we are going to teach the subject, we need to explain what it is. However, we still do not have a single definition of systems engineering that is accepted by all (or even most) systems engineers. In order to resolve this situation we need at least to provide students with an understanding of how the situation arose. This paper now summarises several years of research, discussing the following issues to provide this understanding.

- Multiple definitions of systems engineering
- Origin of systems engineering
- Adjacent and overlapping disciplines

Multiple definitions of systems engineering. (Kasser and Massie, 2001) quoted various definitions of systems engineering and new ones are still appearing. For example (Jain, 2006) defined systems engineering as "*a process that transforms an operational need or market opportunity into a system description to support detail design, its development, production, maintenance, retirement and obsolescence*". Out of more than 50 definitions discovered in the literature (Kasser and Massie, 2001; Kasser and Palmer, 2005), the only one which actually defined systems engineering as a discipline was:

> *"Systems engineering is the intellectual, academic, and professional discipline, the principal concern of which is to ensure that all requirements for bioware/hardware/ software systems are satisfied throughout the lifecycles of the systems. This statement defines systems engineering as a discipline, not as a process. The currently accepted processes of systems engineering are only implementations of systems engineering. . (Wymore, 1994)*

Multiple definitions imply a plurality of views and understandings of the topic. Consider this situation as being similar to the state of the art in chemistry before the development of the periodic table of the elements or the state of electrical engineering before the development of Ohm's Law. This situation typically shows up in the emerging stages of a discipline. It precedes the first step in the scientific method. When we can recognise the situation for what it is, and apply the scientific method, we can make systematic observations and test hypotheses until a generally accepted underlying framework for the discipline evolves, thus expediting the emergence of the discipline. To do that, we need to look at the origin of systems engineering.

Origin of systems engineering. Depending on their perspective, authors have written that the activities performed in producing the ancient pyramids, the canals and railways of the 19th century and other systems of the past are those embodied in systems engineering (Kasser, 1996a) and project management (George, 1972)[1]. The activities in the 1930's that led to the creation of the Air Defence System used by the Royal Air Force in the Battle of Britain have been called systems engineering with hindsight (Haskins, 2006). However, most authors generally agree that systems engineering as a discipline originated during or after World War II although they differ as to

[1] Which discipline they are embodied in, depends on the topic of the book.

exactly when and where it actually originated (Mackey and Mackey, 1994; Hall, 1962; Johnson, 1997; Brown and Scherer, 2000). Thus, systems engineering is indeed in the early years of its lifecycle when compared to established disciplines such as electrical engineering.

Adjacent and overlapping disciplines. There have been many discussions in the literature about the overlapping of, and differences in, the roles of systems engineering, systems architecting, and project management, e.g. (Brekka, Picardal and Vlay, 1994; Roe, 1995; Sheard, 1996; Mooz and Forsberg, 1997);(Kasser, 1996a; Friedman, 2006a; Roe, 1995).

(Mooz and Forsberg, 1997) wrote that systems engineering and project management should be integrated. They state that in many project environments, system engineering and project management are managed separately. This situation is aggravated by the discipline segregation by universities and by the corresponding professional organizations. Because of this separateness, project managers futilely try to manage cost and schedule without managing technical content while the technical providers, ambivalent to the cost and schedule consequences, pursue superior technical solutions.

Research into the origin of the disciplines found the reason for the overlapping disciplines. About 50 years ago, "*driven by cold war pressures to develop new military systems rapidly, operations research, systems engineering, and project management resulted from a growing recognition by scientists, engineers and managers that technological systems had grown too complex for traditional methods of management and development*" (Johnson, 1997). As time went by, practitioners of one of the disciplines would undertake to perform necessary activities that were not being performed in that organisation. However, practitioners of a different discipline would undertake the same activities in a different organisation (Kasser, 2005). As a result, today's organisational paradigm contains three overlapping evolving disciplines (project management, systems engineering and operations research) attempting to solve the same problems from three different perspectives (Johnson, 1997). In small organizations where the work is done by a few people there are generally few problems regarding which person with which job title (role) does what activity (project management and systems engineering). It is only in large organisations where there are a number of project managers and systems engineers that the overlap of roles and responsibilities cause problems. The overlap is expensive due to both the duplication of resources (Friedman, 2006b) and the modern management paradigm that has separated the decision makers from the people who understand the implications of the decisions (Kasser, 1996b). This situation was recognized almost at the dawn of systems engineering by Goode who wrote "*The most difficult obstacle that may be encountered by an [systems] engineer is not the problem but a management which is unsympathetic or lacking in understanding*" (Goode and Machol, 1959) page 513).

WHAT DO SYSTEMS ENGINEERS DO?

This question can be rephrased as 'what is the role of the systems engineer in the workplace?' The literature abounds with discussions on the role of the systems engineer e.g. (Brekka, Picardal and Vlay, 1994; Roe, 1995; Sheard, 1996; Kasser, 1996a; Mooz and Forsberg, 1997; Kasser, 2002; Eisner, 2002; Kasser and Palmer, 2005; Kasser, 2005; Faulconbridge and Ryan, 2003; Maier and Rechtin, 2000; Wymore, 1993) and (Alleman, 2005). Yet what the systems engineer actually does in the workplace does not always fall within the area of activity known as systems engineering. For example,

- (Wymore, 1993) states that systems engineers are problem staters as well as problem solvers. The often-overlooked problem stater role is the critical one of determining the real problem based on stakeholder provided information. The problem solver role maps into the traditional view of the systems engineer as the requirements elicitation and elucidation engineer.
- According to (Roe, 1995) the knowledge and skills of systems engineers are the same as those of project management in the areas of management expertise, technical breadth and technical depth. Roe adds that the difference in application is that the system engineer has more technical breadth, while the project manager has more management expertise.
- (Sheard, 1996) described twelve roles of the systems engineer that are occasionally or frequently assumed to constitute the practice of systems engineering. According to her, some of the roles fit naturally as [system development] life cycle roles, others fit the program management set of roles, while still others are not normally thought of in either group.
- (Eisner, 1997) page 156) expands (Eisner, 1988) and discusses 30 tasks that form the central core of systems engineering. He covers the whole area of systems engineering management in just one of the tasks. Eisner states that "*not only must a Chief Systems Engineer understand all 30 tasks; he or she must also understand the relationships between them, which is an enormously challenging undertaking that requires both a broad and deep commitment to this discipline as well as the supporting knowledge base*".
- (Bottomly, Brook, Morris and Stevens, 1998) studied the roles of the systems engineer and the project manager and identified 185 activities and

their competencies (experience and knowledge). Their findings included:

  - No competency was assessed as being purely the province of systems engineering.
  - There is no sharp division between the two disciplines (systems engineer and the project manager) even at the level of individuals.

- (Kasser, 2005) documented research that separated the role (job) of a systems engineer from the activities in the workplace generally known as systems engineering. The major finding was that the role of the systems engineer and the function or activity known as systems engineering do not overlap 100% so systems engineers do more than systems engineering.

WHAT IS A SYSTEMS ENGINEER?

What is a systems engineer? The simple answer is a person who does systems engineering. However, (Hitchins, 1998) states "*systems engineering ... is a philosophy and a way of life*". Thus interpreting Hitchins, a systems engineer should be a person who lives and acts according to the philosophy of systems engineering. Consider Hitchins' statement as a top-level requirement and derive the next level of requirements by asking, "what are the requirements for a person to be a systems engineer?" To begin the process of answering the question, take up (Kasser, 1995)'s statement that systems engineering covers four dimensions and let a systems engineer be a person who can (and does) intuitively integrate and optimise 'a collection of objects with interrelationships' in four dimensions. The four dimensions are the project, the process, the organisation and time. Examples or use cases of such intuitive behaviour or abilities are:

- Scheduling meetings so that they do not conflict with other meetings. Any time this person arranges meetings, courses, etc, they ensure that the event meshes with existing events.
- Setting schedules so things are done in a logical order in which early activities do not negatively affect later ones, and so that things are not done in a hurry at the last minute. This applies to all types of schedules, not just systems integration.
- Coordinating meetings with external events. For example, research organizations hold periodic meetings. This person tries to set up the program for such meetings that on the meeting before a conference paper deadline, authors get a chance to present their paper to both rehearse the presentation and get comments on it, before the submission deadline, so the presenters can incorporate the often-insightful comments made by their peers into the manuscript.
- Viewing situations both 'as they are', and 'as they could be' at the same time. This person can walk into a situation and point out improvements using this ability. For example, in a conference setting, the presenters were having a problem pacing their presentations to keep time. This person would ask the conference organizers to put a clock on the wall at the back of the room to enable the presenters to invisibly pace themselves (provided that the clock was pointed out to them before they began their talk).
- Being able to examine problems from more than one perspective (most of the time). These perspectives have called cognitive filters in the behavioural science literature, e.g. (Wu and Yoshikawa, 1998), and decision frames (Russo and Schoemaker, 1989) in the management literature. Whatever we call them, they are the internal filters through which we view the world. They include political, organizational, cultural, and metaphorical filters, and each of them highlights relevant parts of the system and hides (abstract out) the parts not relevant to the filter.
- Being able to act as a catalyst (Demarco, 1997) to invisibly resolve system and process related issues speedily and peacefully.
- Being able to challenge assumptions by asking disconfirming questions (Russo and Schoemaker, 1989) page 103) or good questions (Frank, 2006) to identify and then state the real problem (Wymore, 1993). The ability to pose these questions may stem from the ability to view a situation from an alternative perspective.
- Making use of lessons learned by others before starting a new project. This person may make mistakes, but at least they will be new ones.
- Being able to quickly determine the aspects of a situation which are relevant to the problem, or, in electrical engineering language, separate signals from noise.

These abilities (described in the form of scenarios or use cases) link back to the Hitchins' top-down definition but do not seem to implicitly link to the commonly accepted domain knowledge of systems engineering taught in academic institutions. This linkage may however be seen from a bottom-up perspective. From a bottom-up perspective, the literature contains several publications on the characteristics of systems engineers. For example, (Hall, 1962) pages 16-18) provided the following specifications or traits for an "Ideal Systems Engineer" grouped in the following areas:

- An ability to see the big picture.
- Objectivity.
- Creativity.
- Human Relations.
- A Broker of Information.
- Education - Graduate training in the relevant field of interest (application), as well as courses

in probability and statistics, philosophy, economics, psychology, and language.

- Experience in research, development, systems engineering and operations.

Hall concluded by stating that the ideal is not available because the scope of the task is beyond the capabilities of a single individual, mixed teams of specialists and generalists are used. Later bottom-up studies include (Frank, 2002) and (Frank, 2006) who consolidated and classified the characteristics of successful systems engineers as ten cognitive characteristics, eleven abilities, ten behavioural competences and fifteen dealing with knowledge.

THE CONTEXT MAP

The answers to the three questions show that systems engineers do more than systems engineering and hence need the knowledge and skills to perform as both engineers and managers in any area of activity that lies within the area of activities involved in creating and maintaining systems. This means that we need a framework for defining the requirements for what is to be taught. Such a framework already exits. (Kasser and Massie, 2001) developed a two dimensional framework for a body of knowledge for systems engineering using Hitchins' five layers (Hitchins, 2000) as the vertical axis and the stages of the system lifecycle as the horizontal axis.

The vertical axis splits the broad range of activities encompassed by the term systems engineering into the following five nested layers:

Layer 5 – Socio-economic, the stuff of regulation and government control.

Layer 4 - Industrial systems engineering or engineering of complete supply chains/circles.

Layer 3 - Business systems engineering - many businesses make an industry. At this layer, systems engineering seeks to optimise performance somewhat independent of other businesses.

Layer 2 - Project or System layer. Many projects make a Business. Western engineer-managers operate at this layer, principally making complex artefacts.

Layer 1 - Product layer. Many products make a system. The tangible artefact layer. Many engineers and their institutions consider this to be the only "real" systems engineering.

Hitchins stated that the five layers form a "nesting" model, i.e. many products make a project, many projects make a business, many businesses make an industry and many industries make a socio-economic system. Hitchins adds that clearly, these statements are only approximate since-

- A socio-economic system has more in it than just industries.
- A business has more in it than just projects, and so on.
- Actual organizations may divide the work in different ways resulting in either sub-layers, or different logical break points.

The horizontal axis covers the phases of the system lifecycle which have been stated in various ways in various standards, conference papers and books, but for this framework they are defined in generic terms in (Kasser, 2006) as:

A. Identifying the need.
B. Requirements analysis.
C. Design of the system.
D. Construction of the system.
E. Testing of the system components.
F. Integration and testing of the system.
G. Operations, maintenance and upgrading the system.
H. Disposal of the system.

The vertical and horizontal axes produce a two-dimensional map containing 40 areas as shown in Figure 2. Thus, a systems engineer performing requirements analysis for a system would be working in Area '2B'. Another systems engineer performing integration testing on another system would be working in Area '2F.'

Layer of Systems Engineering \ Phase in the Life Cycle		Needs identification	Requirements	Design	Construction	Unit testing	Integration & testing	O&M, upgrading	Disposal
Socio-economic	5								
Supply Chain	4								
Business	3								
System	2								
Product	1								
		A	B	C	D	E	F	G	H

Figure 2 The HKM Framework

The Hitchins-Kasser-Massie (HKM) Framework provides the context for the body of knowledge and skills needed by systems engineers working (determining and solving problems) in the different areas of the framework. What is still needed is a way to organise the knowledge in a practical manner. The answer may lie with Wymore's concept of systems engineering as a problem determining and solving discipline (Wymore, 1993) and (Mar, 1994) who discussed *"four basic steps that are used repeatedly to describe the development of an answer to any type of problem, whether it is a top level mission analysis* *or a bottom level maintenance task. These four basis steps are:*

FUNCTIONS – Define what functions the solution must perform.
REQUIREMENTS – Define how well each function must be performed.
ANSWERS – Search for a better answer and manage risk associated with that answer.
TESTS – Demonstrate that the answer performs the needed functions."

Mar labelled these steps as FRAT from the first letter of each step. Each step of the FRAT incorporates problem solving, but the type and scope of the problems being solved, and hence the methodology adopted will be different in each area of the framework. If FRAT is considered as a meta-methodology for what is done, then how each step is done will depend on the area of the framework and there are a broad range of applicable tools and techniques already existent in the literature that can be taught.

(Kasser, 2007) showed that the HKM framework allows systems engineering to meet the requirements for a disciple as defined by (Kline, 1995). The framework coupled with Mar's FRAT meta-methodology should provide the basis for developing the requirements for the knowledge needed by practitioners in each area of the framework as well as the type of knowledge to be taught in introductory courses in systems engineering. This brings us to the subject of teaching and learning

TEACHING AND LEARNING

Teaching and learning are about the transfer of knowledge from the teacher to the learner. In order to optimize this transfer, we first have to understand the learning process then look for ways to optimize it. There are several ways of classifying knowledge including:

- General and specific knowledge, and
- Declarative, procedural and conditional knowledge

General and specific knowledge. "Knowledge emphasises understanding of concepts and theories in different subject matter domains and general cognitive abilities, such as reasoning, planning, solving problems and comprehending language" (Greeno, Collins and Resnick, 1996) quoted in (Woolfolk, 1998). Thus, some knowledge is general and some is domain specific.

Declarative, procedural and conditional knowledge. This classification can be found in (Woolfolk, 1998), where:

- **Declarative knowledge** is knowledge that can be declared in some manner. It is "knowing that" something is the case.
- **Procedural knowledge** is "knowing how" to do something and must be demonstrated. Thus, for example, describing a process is declarative knowledge. Performing the process demonstrated procedural knowledge.
- **Conditional knowledge** is "knowing when and why" to apply the declarative and procedural knowledge.

Moreover, concepts within cognitive psychology have major implications on the process of education. (Bruning, Schraw, Norby and Ronning, 2004) present seven themes from cognitive psychology that are relevant to teaching and learning. These are:

1. Learning is a constructive not a receptive process.
2. Mental frameworks organize memory and guide thought.
3. Extended practice is needed to develop cognitive skills.
4. Development of self-awareness and self-regulation is critical to cognitive growth.
5. Motivation and beliefs are integral to cognition.
6. Social interaction is fundamental to cognitive development.
7. Knowledge, strategies, and expertise are contextual.

The literature also contains a number of suggestions for what can be incorporated into the classroom experience. For example:

- (Brown and Scherer, 2000) suggest incorporating the following features into the classroom experience:

    1. use of open-ended problems;
    2. encouragement/development of student creativity;
    3. use of the systems design methodology;
    4. consideration of alternative solutions;
    5. detailed system design specifications;
    6. use of decision methodologies;
    7. consideration of feasibility, reliability, and maintainability;
    8. inclusion of economic, social, ethical, aesthetic, and economic impacts;
    9. use of real problems with real clients.

- (Sage, 2000) cites (ASEA, 1994) which suggested that the ingredients associated with reshaping the curriculum were:
    1. team skills, and collaborative, active learning;
    2. communication skills;
    3. a systems perspective;

4. an understanding and appreciation of diversity;
5. appreciation of different cultures and business practices, and understanding that engineering practice is now global;
6. integration of knowledge throughout the curriculum a multidisciplinary perspective;
7. commitment to quality, timeliness, continuous improvement;
8. undergraduate research and engineering work experience;
9. understanding of social, economic, and environmental impact of engineering decisions;
10. ethics.

The pedagogy also needs to take into account the retention information by students varies according to the delivery method. According to the often quoted learning pyramid from the National Training Laboratories, Betel, Maine (Lowery, 2002), shown in Figure 3, lecturing is the worst way teach, yet many of our classes are still in that format and students complain of ‘death by PowerPoint”. Many distance education classes still consist of mostly readings, the second worst way to teach. We need to change the pedagogy of both the face-to-face and distance learning classrooms to maximise, or at least increase the retention rate. So as well as reviewing the literature, the actual experience of changes in the pedagogy of teaching software maintenance via distance learning (Kasser and Kirby, 1999) will be considered when developing the requirements for the pedagogy.

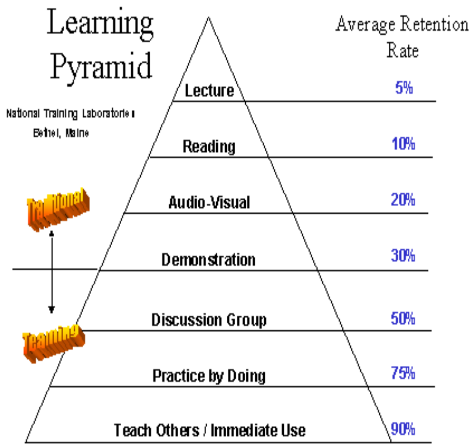

Figure 3 The Learning Pyramid

DISCUSSION

This paper has discussed some of the initial set of requirements for introductory courseware in systems engineering based on the three questions and factors that make learning effective. Further requirements come from experience, such as teaching software maintenance (Kasser and Kirby, 1999) and the lessons learned from crafting degrees for industry and government (Kasser, et al., 2004).

Current books and other publications tend to present systems engineering from a single perspective – that of the author. Research has shown that much of the confusion about the nature of systems engineering and the roles and activities performed by systems engineers are the result of viewing the situation from a single perspective. Moreover, each person has a different single perspective! This situation is reflected in the current generation of courseware, which perpetuates the situation, resulting in a closed loop. Moreover, in the postgraduate course, the emphasis must be on conditional knowledge, since the application of conditional knowledge demonstrates mastery of the subject. Yet we find that much of systems engineering is taught as declarative and procedural knowledge, namely how to perform the process of systems engineering.

SUMMARY

This paper set out to determine the scope for the requirements for the content of introductory courseware in systems engineering. Beginning by stating the apparent current confusion within the discipline, the paper continued with a brief outline of a tested process for creating courseware. The paper then discussed developing the initial set of requirements for the knowledge and skills component of the courseware and used the HKM framework as a context map to identify the knowledge and skills needed by systems engineers. The paper then scoped further requirements for expediting learning based on cognitive psychology principles and factors that make learning effective. Lastly the paper identified other sources of requirements and a source of confusion about the nature of systems engineering and came to the conclusion that the current generation of courseware perpetuates the confusion.

CONCLUSIONS

The conclusions are:

1. The current curriculum of introductory systems engineering courses perpetuates the apparent current confusion about systems engineering amongst its practitioners.
2. A new set of courseware is required that breaks the circle and creates potential future systems engineers with the knowledge and skills they will need to perform effective systems engineering. The activities comprising systems engineering and project management are generally the same and constitute decision-making and problem solving. Thus, introductory courseware in systems engineering needs to

   (a) Cover the appropriate elements of the traditional curriculum content covering the systems life cycle.

(b) Incorporate appropriate techniques from cognitive psychology.
(c) Focus on the development of problem stating and solving skills and the place of different types of systems engineering in the HKM framework.

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BIOGRAPHY

Dr. Joseph Kasser has been a practicing systems engineer for more than 35 years. He is an INCOSE Fellow and the author of "Applying Total Quality Management to Systems Engineering" and many INCOSE symposia papers. He holds a Doctor of Science in Engineering Management from The George Washington University, and is also a Certified Manager. He is Deputy Director and an Associate Research Professor at the Systems Engineering and Evaluation Centre at the University of South Australia. He teaches online and in the classroom as well as performing research into the nature of systems engineering and the properties of object-oriented requirements. He is a recipient of NASA's Manned Space Flight Awareness Award (Silver Snoopy) for quality and technical excellence for performing and directing systems engineering and many other awards and commendations.