Educating Systems Engineers: Encouraging Divergent Thinking

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Abstract. Parallels between divergent thought processes, studied in creativity research by developmental psychologists, and the intellectual control imperatives of systems engineering are examined. A metaphorical template of the systems engineer's thought processes as defined by and taught from the standpoint of convergence is presented, and a core set of training modules to aid in evolving systems engineers from domain engineer stock is recommended. A. D. Hall's 1969 model of the systems engineer's thought structure is resurrected and is found to still apply to the convergent mode of systems engineering training. It is suggested that teaching systems engineers to develop divergent thought processes is analogous to teaching "creativity" in other fields. An examination technique, employed with success in a related field (e.g., Microsoft certification), that uses the traditional "convergent" multiple choice question, but forces divergent thinking to arrive at the "correct" answer, is discussed.

SYSTEMS ENGINEERING EDUCATION IS DIFFERENT

Background. Systems engineering has unique education needs compared to other engineering disciplines.

> *"Systems engineering practitioners think in fundamentally different paradigms from (domain) engineers. Because almost all engineers are initially trained in a domain specialty, systems engineers typically 'grow' from within an organization."* (Friedman 1994)

In the world of engineering, some flourish by becoming in-depth experts in a technology, others flourish by expanding their range of consideration to the boundaries of a problem. The former set are labeled "domain engineers," the latter "systems engineers." Because the thought processes required by the two disciplines are different, each set of practitioners must be trained to enhance the characteristic thought processes of its discipline.

At the undergraduate level, most if not all engineers are trained to be domain engineers. It takes about five years of industrial maturity to lead domain engineers into systems engineering (Friedman 1994). Focus must be applied more on the whole, with its synergism and conflict, than on individual domain technologies.

So how does an engineer five years beyond a bachelor's degree get trained in a fundamentally different craft? "In attempting to develop graduate level curricula in systems engineering, it has been found that systems engineers cannot be effective until a substantial base of industrial maturity (about five years) is attained, This reinforces the observation that undergraduate engineering curricula do not address the extensive thought processes needed by systems engineers; concentrating, rather, on problem solving techniques" (Friedman, 1994).

Demands on systems engineering are not the same as demands on domain engineering. The systems engineer must be aware of, if not actually understand, all facets of the solution to the problem at hand, whereas a domain engineer must understand a narrow technology in great depth.

For a given design problem, the systems engineer first thinks of all the things that can go wrong. The domain engineer thinks of all the things that must go right. Dick (1994) describes the systems engineering thought process

> *"At each step in the development cycle, Systems Thinking addresses the full spectrum of product objectives. It then stimulates and guides the generation of new ideas. Next, it helps you selectively evolve the best concepts while simultaneously mitigating risk. Then it uses fault analysis to help you pinpoint weak areas and therefore incorporate features into your ideas that will assure success."*

The education of the systems engineer must reinforce the broad view of a problem solution (Dick 1994, Friedman 1994, Ball et al 1999).

Ring and Wymore (2000) wrote about the

"Practitioner of Systems Engineering" [PSE] providing a common vocabulary to further communications among participants. In presenting an overview of a concept of operations for an SE Education community, they assert that

> *"…improving systems engineering must be done by improving one or more PSEs, be they project practitioners, employer managers[,] or provider principals, and doing so in a way that causes the resulting system to exhibit improved effectiveness rather than exhibiting conflicts and diminished performance"* (Ring and Wymore 2000).

Psychologists refer to the thought process of systems engineering as being "divergent" and the thought processes of domain engineers as being "convergent" or "reductionistic" (Gale Group, 2000).

The field of developmental psychology can help engineering education theorists to gain a qualitative grasp of divergent thought processes and convergent thought processes.

Divergent thought processes. Gale Research reported that

> *"The concept of divergent thinking was developed in the 1950s by psychologist J. P. Guilford, who saw it as a major component of creativity and associated it with four main characteristics."* (Gale Group 2000)

These characteristics are shown in Table 1.

Table 1: Characteristics of Divergent Thinking

Guilford's Characteristics of Divergent Thinking	
Fluency	"The ability to rapidly produce a large number of ideas or solutions to a problem"
Flexibility	"The capacity to consider a variety of approaches to a problem simultaneously"
Originality	"The tendency to produce ideas different from those of most other people"
Elaboration	"The ability to think through the details of an idea and carry it out"
Source: Adapted from (Gail Group 2000)	

Traditional engineering education concentrates on recognizing problem forms and selection of an appropriate solution method. Little education is provided in how to set up problems.

Systems engineering, following the divergent thought process, first seeks to establish a boundary within which the solution must be contained, then to conform the problem solution to its boundary.

The systems engineer will specify the interfaces and transfer function of (for example) a chip set, including what it must do, how well it must do it, and under what conditions, including the regularities of the universe associated with the intended deployment of the system (temperature, pressure, electromagnetic field intensity, heat flow paths, and so on).

Working within the interface and transfer function constraints, domain specialist engineers then develop this part of the problem solution.

Convergent thought processes. The Gale Group wrote,

> *"Convergent thinking, which narrows all options to one solution, corresponds closely to the types of tasks usually called for in school and on standardized multiple-choice tests. In contrast, creativity tests designed to assess divergent thinking often ask how many different answers or solutions a person can think of to a specific question or problem. Some researchers have claimed that creative achievement actually involves both divergent and convergent thinking--divergent thinking to generate new ideas and convergent thinking to 'reality test' them in order to determine if they will work."* (Gale Group 2000)

Most college education in engineering focuses on identification of problem patterns and memorization of solution methods. All engineers begin in the comfort zone of defined parameters and solution types. Later in a career, some will choose to go to great depth within a narrow domain; others will choose to expand laterally to the boundaries of the problem space.

Unfortunately, the need to "…get something done…" often leads to the development of a solution before the requirements are defined. In other words, there is a high probability that a solution will search for a problem that it fits.

Convergent thinking is essential to filling in the blanks on a system diagram with real hardware and real software. The systems engineer, with the broad view, cares only that the transfer function and design interfaces of each piece are maintained. How each piece is done is the province of convergent thinkers.

CREATIVITY AND DIVERGENT THINKING

We assert that systems engineering invokes the same thought processes that Guilford associated with creativity.

> *"Divergent thinking -- the type that Guilford associated with creativity -- entails the ability to envision multiple solutions to a problem."* (Gale Group 2000).

Consider the observation that system engineers invariably move to the consideration of things that can go wrong with a proposed system design solution. This is an application of Guilford's concepts of fluency and flexibility.

> *"Fluency is the ability to rapidly envision a*

number of different ways to solve a problem. Flexibility refers to the ability to consider various alternatives at the same time." (Gale Group 2000)

In the ideal sequence, the systems engineer starts with an operational need and a blank sheet of paper. The first efforts are associated with exploring the solution space, assessing, evaluating, and discarding various approaches to solving the system design problem.

In the usual, less-than-ideal sequence, the operational need is associated with a proposed solution. The systems engineer envisions the implications of the proposed solution in the light of fluency and flexibility and quite often responds with questions that begin, "Have you thought about…?"

This apparent lack of immediate and enthusiastic acceptance of the proposed solution sometimes causes the systems engineer to be declared to not be a "team player."

SYSTEMS THINKING

Perception and reality. Systems engineers are required to know the WHY as well as WHAT, HOW, and HOW WELL of a problem solution.

The WHY behind a constraint on the problem solution often has no relationship to truth or reality. To provide adequate design, the systems engineer must separate truth from fiction.

Design to truth and you will always be safe. Design for perception and you will eventually be clobbered. Systems engineers must be educated to find and understand real reasons (the WHY).

It has been determined by developmental psychologists that between the ages of four and four-and-a-half, most children develop a "Theory of Mind," that is, the ability to differentiate between what one knows to be true and what one thinks another believes to be true.

Suddendorf and Fletcher-Flinn (1997) speculate,

"The development of a 'theory of mind' may not only be important for understanding the minds of others but also for using one's own mind…."

This may explain the easy acceptance of the patently absurd assertion, "Perception is reality." It is of little consequence that another person believes that perception is reality, as long as one knows the reality, except when the absurdity is held to be true as an article of faith by a person one is attempting to train.

The critical factor is that people holding the false belief that perception is reality sometimes by virtue of vested authority can force a system design toward accommodating perception, while reality lurks in nature. Nature of course has the deciding vote.

"Only when the representational nature of mind is understood may one truly reflect and introspect, that is, form beliefs about beliefs (e.g., I must be right with my view that...), attitudes about knowledge (e.g., I don't want to know), second-order motives (e.g., I don't want my desire to play to interfere with my work), and so forth. It might thus be expected that skills that apparently depend upon mental access to one's own mind (e.g. knowing that and what one knows) improve dramatically with the acquisition of a [theory of mind.]" (Suddendorf and Fletcher-Flinn 1997).

Thinking outside the four dots. A classic parlor game is to lay out four dots on a sheet of paper, roughly at the corners of a square (Figure 1), and challenge a person to draw three straight lines through all four dots without the pencil leaving the paper or crossing the trace. When presented with just the four dots, most people will assume the implied lines between the dots form a boundary to the solution and become frustrated that a continuous line cannot be drawn to touch all four dots without crossing its trace. The solution thus must lie outside the four dots. Analogously, systems engineers (divergent thinkers) must *always* think outside the four dots.

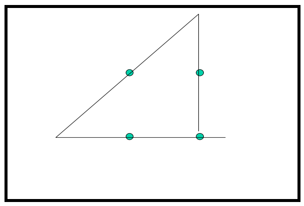

Figure 1. Solution to the Four-Dot Problem

The solution to the "four-dot problem" is shown in Figure 1. Try the same problem with nine dots in a 3 x 3 array, but allow the pencil to cross its trace one time.

Suddendorf and Fletcher-Flinn [1997] observed

"Divergent thinking might be such a skill. Several researchers have identified metarepresentation as an important factor in creativity. Determining whether possible solutions fulfill the criteria of the problem, for example, might be a function of metacognition.... Divergent thinking by its very definition appears to require the individual to search his/her own knowledge base beyond the currently activated domain of mental content. This may entail the same basic process of executive control or disengagement from current perceptions and knowledge as is required for assuming a belief that is evidently false. On a higher plane (at a later age) disengaging from a current paradigm and 'investing' in disregarded areas is, of course, the key to

creative new insights.... Further, active scanning of one's knowledge base in search of appropriate answers appears to imply the ability to metarepresent (i.e., to know what one knows). Knowing what others know... and knowing what oneself knows might be very closely related skills. Indeed, some might suggest that the former is an extension of the latter....”

Societal baggage: Systems engineering education at one major aerospace firm is designed for engineers that have at least five years industrial maturity. Some appreciation for the way the industrial world works is a prerequisite.

In the last decade, one large government contractor attempted to educate new college graduates who didn’t have the industrial world-view or the maturity to separate truth from clever fiction. These students often fell back on the societal baggage that has been handed down through unchallenged prejudice and pithy buzzwords. Many missed the point of systems engineering altogether. They should all have memorized the following proverb.

“He who knows not, and knows not that he knows not, is a fool. Shun him.
He who knows not, and knows that he knows not, is simple. Teach him.
He who knows, and knows not that he knows, is asleep. Wake him.
He who knows, and knows he knows, is wise. Follow him.” (Various sources)

Truth. Will Rogers observed, “It ain't what you don't know that'll hurt you - it's what you do know that ain't true.” The systems engineer is compelled to challenge policies and practices that impede rather than enhance development of a problem solution. Thus, systems engineering education must stretch the minds of the students. The systems engineer must understand the WHY in order to make rational design decisions.

Political correctness. Some students belong to one or more of a number of loudly vocal groups with secondary agendas that tend to impede learning. In teaching the system engineer to think outside the dots, conflict with these secondary agendas is inevitable. The wrong solution is to avoid the issues; the right solution is to examine the issues in search of the truth. Immature students will find it difficult to part with their pre-judgments.

Chronological age does not guarantee that an individual possesses the metarepresentational skills needed for a "Theory of Mind." Lack of the ability to make objective assessment of pre-judgment indicates lack of ability to metarepresent -- to know what oneself knows. Suddendorf and Fletcher Flinn [1997] suggest that “knowing what others know” may be an extension of “knowing what oneself knows.” Metarepresentation is critical to divergent thinking; and divergent thinking is critical to systems engineering, thus lack of metarepresentational skills indicates probable inadequacy as a systems engineer.

INTELLECTUAL CONTROL OF THE PROBLEM SOLUTION

The global view. The systems engineer maintains the global view of the problem. The person exercising intellectual control over the problem solution is the Systems Engineer, although that person might carry any of a number of titles that mean ”Chief Technologist.”

A wise program manager entrusts the stewardship of the technical integrity of the problem solution to the systems engineer.

The systems engineer establishes the boundary about a system and performs the first level partitioning of the solution within that boundary. Once the partitions are agreed, the systems engineer monitors design of the entities that will implement the partitioned functions for compliance to interface and transfer functions. In attending to these operations, the systems engineer calls upon the domain engineers, as they are needed, to add flesh to the skeletal design.

The systems engineer and domain engineers. Dr. Glynn Lunney, at one time Director of the Space Shuttle Program at the Johnson Space Flight Center observed,

“If we consider all technology as a barrel of water, I can find a domain engineer to cover any square inch of its surface and plumb the depths below that area. What I can’t find is the engineer that can cover the entire surface of technology like a single drop of oil” (Lunney 1983).

We must train our systems engineers to perform the function of that single drop of oil.

Two questions deep. The systems engineer must be at least two questions deep in any technology that is relevant to the problem solution at hand. The first question is “Does this technology relate to my problem or to its solution?" Question two asks, “What is the phone number of an engineer who knows this technology in depth?”

Systems engineering orchestrates domain-engineering specialties in pursuit of a joint problem solution.

The systems engineer as coordinator of domain technologies. In-depth technical knowledge resides within the specialized domains. The role of the system engineer is to identify when the specialty domains are needed and to coordinate their participation in developing the design solution.

It is both arrogant and dangerous for system engineers to assume they know enough to complete the detailed design without consulting domain experts.

Thus, the role of systems engineering is to define the work and invoke experts as needed; to orchestrate the problem solution.

Successful systems engineers know "whom to call about what, and when." An address book is helpful, but participation in the phase of a system development where all technologies are involved (such as proof-of-performance test) is needed to provide knowledge of expected interactions.

Perception and reality (again). A frequently heard phrase is, "Perception is reality." To accept that idea at face value is to put one's intellect on hold. "Perception" is individualized and subjective. Perception sometimes represents reality, but not always.

"Reality," on the other hand, is always true, solid and invariant, and no spin on perception is going to change it. The systems engineer must be trained to challenge assumed truths and find the underlying reality.

SYSTEMS ENGINEERING EDUCATION

It is anticipated that most students will enter systems engineering education with a traditional engineering education background. This establishes a starting point for in-house education. Therefore, it is important to anticipate the level of preparation that the students bring to the systems engineering class.

University engineering education. We can expect the recent engineering graduate to enter industry capable of expressing ideas in written, oral and graphical form, well supported by a solid foundation in mathematics, the sciences and humanities, with at least an appreciation of systems concepts.

The goal of industrial education for systems engineers is to identify divergent thinkers and pipeline them into system engineering positions. Convergent thinkers move on to success as domain specialists.

Divergent thinkers become systems engineers because they intuitively understand the compromises involved in optimizing a solution having multiple system performance objectives. They sense how to effectively merge the contributions of the engineering specialty domains.

A Convergent Approach to Training Systems Engineers. Figure 2 illustrates the interactions and considerations the systems engineer must be trained to carry in his head.

The entries along the **Logic** axis correspond to the usual systems engineering decision time line. Along the **Phases** axis, the entries reflect the usual DoD project life cycle. Along the **Knowledge/Skills** axis, the entries list the intellectual properties that must be considered in each analysis. The systems engineer must understand the nature of this triad.

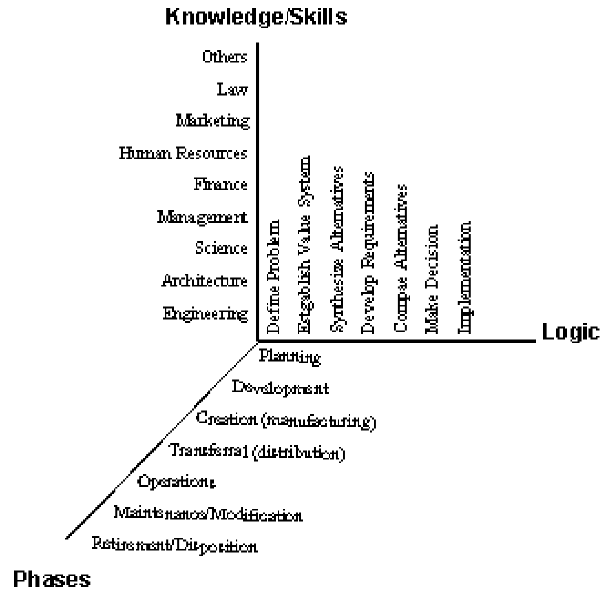

Figure 2. Systems Engineering Thought Structure (Hall 1969)

Any 3-tuple defines a systems engineering activity. Training of systems engineers must provide the organization and intellectual tools to deal with problem elements in 343+ discrete cubes.

Pick a triad, say, **Develop Requirements** (along the **Logic** axis)**, Transferal** (along the **Phases** axis), and **Finance** (along the **Knowledge/Skills** axis). Hold any two constant and examine the implications of the third. For example, holding the **Logic** and **Phases** selections constant examine the implications of all entries on the **Knowledge/Skills** axis leads to the following.

Hold "Develop Requirements" and "Transferal (distribution)" constant. Now examine the remaining axis.

Possible questions are:

1. Requirements for engineering the transferal subsystem: packaging, transportation, shock and vibration isolation, etc.

2. Requirements for architecture consistent with the transferal subsystem: modularity, ease of disassembly and reassembly, test and evaluation, etc.

3. Requirements for a scientific base for the transferal subsystem: environmental impacts, nuclear hardening, out-gassing, pressure, acceleration, etc.

4. Requirements for management of the transferal subsystem: transport vehicles, licenses, clearances, pilots (drivers), Hazmat registration, etc.

5. Requirements for financing the transferal subsystem:. budget, insurance, cost per unit distance, uplift to cover civil liability, cash flow, etc.

6. Requirements on human resources to affect the transferal subsystem:. operators, organized labor constraints, OSHA restrictions, skills, etc.

7. Requirements under the relevant laws of areas traversed by the transferal subsystem:. patents, intellectual property, copyright, foreign technology transfer, etc.

A Divergent Approach to Training Systems engineers. The Gale Group (2000) observed,

> *"Although creativity is associated with the highest levels of achievement in many fields and presumably valued by society, the educational system often penalizes divergent thinkers. The typical standardized measure of intelligence is the multiple-choice test, which is diametrically opposed to the divergent thinker's problem-solving process. To a creative thinker, it may seem more productive to try finding reasons why all the choices on a multiple-choice question could be correct than to select the preferred answer. In addition, most classroom teaching is heavily biased toward the learning style of convergent thinkers, a fact that helps explain the dismal school performance of such legendary geniuses as Albert Einstein and Thomas Alva Edison, who was considered retarded and expelled from school. Creative children easily become bored in situations where uniform responses are expected and the product of intellectual effort is emphasized over the process. Instead of answering questions correctly, divergent thinkers are likely to provide additional answers of their own or even challenge the questions themselves, responses that teachers may consider inconvenient, uncooperative, and a threat to their authority."* (Gale Group 2000)

If the skills demanded of systems engineers are similar to the skills of creative efforts, then, by analogy, the training of systems engineers should parallel the training of creative people.

> "*Creativity has been the subject of intensive research since the 1960s. As a result, we are increasingly able to identify the behavioral factors that are common to unusually inventive individuals, as well as the environmental factors that contribute to creative thinking and creative problem-solving*" (Libby 1984).

Researchers have studied creativity from the perspective of process, personality characteristics of creative people, and environmental conditions that promote creative activity (Libby 1984).

Process. Libby writes, "Experts on creativity [Guilford 1973] generally agree on the phases a person goes through in the creative process.... These stages are not necessarily distinct and usually involve a complex recycling of the process." Table 2 lists these phases.

Table 2: Phases in the Creative Process

Guilford's Phases in the Creative Process	
Preparation	"Acquiring skills, background information, resources, sensing and defining a problem"
Concentration	"Focusing intensely on the problem to the exclusion of other demands -- a trial and error phase that includes false starts and frustration"
Incubation	"Withdrawing from the problem; sorting, integrating, clarifying at an unconscious level; often includes reverie, relaxation, solitude"
Illumination	"The Aha! stage, often sudden, involving the emergence of an image, idea, or perspective that suggests a solution or direction for further work"
Verification, Elaboration	"Testing out the idea, evaluating, developing, implementing, convincing others of the worth of the idea"
Source: Adapted from (Libby 1984)	

> "*According to the most extensive research in this field, creative people possess in quantity the abilities identified by Torrance* [listed previously in Table 1]*: sensitivity to problems and deficiencies; ability to flesh them out; and ability to perceive in a way different from the traditional or established method. In addition, highly creative people share the following traits: flexibility rather than rigidity, openness to new ideas and experiences, tolerance of ambiguity, a wide range of interests, curiosity, enthusiasm and energy, vivid imaginations, playfulness, commitment and concentration, comfort with change, capacity for hard work, persistence, divergent thinking. Because creativity involves new approaches and the production of something new and untried, it also involves the risk of failure. It follows logically, then, and is supported in the literature, that two characteristics of the creative person are particularly significant: self-confidence, based on a strong self-concept, and independence, the strength to hold fast against disagreement or resistance by others and the courage to persist when others may be threatened by a new idea or discovery.*" (Libby 1984)

Cropley and Cropley (2000) state,

> *"Current practice suggests that creativity and innovation (C&I) is largely regarded as a black art, possessed by some, and not by others, Companies may pay lip service to the need for*

C&I or may even regard themselves as paragons of C&I, yet frequently this is the result of individual 'champions' rather than a systematic, cultural adherence to C&I in work practices and education."

They continue to present and detail a model of creativity and innovation for systems engineering. A future paper will adapt the Cropley model to specific steps in the author's approach to graduate systems engineering education. (Cropley and Cropley, paper in process)

Training it in. Anecdotal evidence suggests that a bane of many creative students (and thus also of system engineers) is the multiple-choice test of the type used on standardized tests. However, multiple-choice questions can and have been formulated in ways that force creative thinking. The usual multiple-choice question consists of one correct response and three or four options that are obviously incorrect; if one knows the answer, mark the square and move on without reflection.

The form of multiple-choice question adopted in some systems engineering classes at the Graduate School of Management and Technology at the University of Maryland University College allows any combination of answer selections, and any number of choices (not just a fixed number for all questions), so that successful guessing is less likely. The questions are designed such that the correct answer can only be deduced by eliminating the incorrect answers. Selections such as "answer a and answer b only" are particularly good at negating guessing. Students are encouraged but not required to write detailed explanations of their answers; these answers, if skillfully written, can get them credit even with their barebones answer might have been incorrect (with references if desired) Skills required for each question, in addition to the multiple systems engineering concepts each question will typically publish, include: logical thinking, attention to detail, research (since the tests are take-home), and the use of a methodological approach to make sure no possibilities are overlooked; all of these are valuable systems engineering skills. Outside support for this style of question was gained from the success of Microsoft's certification program, which uses similar questions. (Microsoft 2001)

Systems engineering training materials are presented in the usual convergent way, but examinations and self-tests are designed to stretch the student's imagination. [One student, part of a group of three successful mid-career systems engineers working together on a multi-billion dollar military project, commented that he and his two fellow students found the test "was a learning experience that stretched the mind; the research required to determine the best answers was very rewarding (Johnson, 2001)."]

The key characteristics of fluency, flexibility, and originality are extended by essay-type assignments. Favorable results have been gained by requiring students to read quotations from Morris Asimow's 1962 classic, :*Introduction to Design*, research the topics, and to either support or to refute the 1962 thinking in the light of current technology.

Experimentation with fluency assessment and flexibility assessment of systems engineering students is continuing in the current academic year.

CONCLUSIONS AND RECOMMENDATIONS

In the discussion of teaching systems engineering as a convergent process, a metaphorical template of a systems engineer's thought process was given. If educators are to train systems engineers to follow that philosophy, there are two options. A teacher can create 343+ modules and teach each in isolation, or can partition the space into technology-based sets. Partitioning is preferred because the concepts are mutually supportive, making for an easier learning experience. A possible set of technology-based courses is the following:

Fundamental Principles and Practices
Decisions and Trade Studies
Inspection processes
Requirements development
Integration and Test Technology
Systems engineering capability maturity
Performance analysis
Integration of off the shelf (COTS) subsystems

These courses may be taught at any level to any student with basic preparation. The danger in partitioning is that it is easy to lose sight of the global intellectual control mandated on the practice of systems engineering. Teach the partitioned material, but don't forget the global imperative. Occasionally dusting off Figure 3 and applying it to the problem has yielded good results.

In assessing the implications of Suddendorf's treatment of the "Theory of Mind" it is observed that some people don't know that they don't know. The observer may feel, for example, that the person knows that the expression, "Perception is reality" is absurd, but in fact the person may actually believe it to be true. This poses particularly difficult conditions on an instructor because the person may take an absurdity as an article of faith.

In the discussion of teaching system engineering as a sequence of exercises in developing characteristics of creativity, a set of characteristics to be trained into the student was asserted, and an approach indicated. Much work remains to be done in melding the knowledge base (trained in by convergent methods) with the divergent thought characteristics (trained in by associative methods).

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