Divergent Thinking in Systems Engineering Practice: Is There a Shortfall?

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Abstract. Divergent thinking produces an expanded definition of both problem and solution space. Convergent thinking leads to the selected solution. A balance of the two is an essential element of effective systems engineering practice. A significant predominance of convergent thinkers and shortage of divergent thinkers has been noticed in a group of systems engineering students. A negative impact on exercise results was also noticed. If this is a valid observation of the general systems engineering field, there are serious implications that must be addressed in training and at work. This paper outlines the initial observation, impact, and potential for future research.

Introduction

The first indication. The author has been teaching systems engineering for over 20 years in courses that use reasonably complex problems for the in-class exercises. In that time, a feeling has been developed about the amount of time it takes to do each exercise and the types of results that should be expected. It was a surprising development when one class repeatedly finished the exercises in a quarter to half of the time expected. The results reflected the time spent in the depth of analysis. As a result, the approach to the exercises changed to use the remaining time for instructor led depth of analysis and consideration of alternatives.

Near the end of the course is a lesson on personality impacts on systems engineering using Myers-Briggs personality types. One of the factors in MBTI is related to the preference for convergent thinking or divergent thinking. It was discovered that this particular class was absent of any members preferring divergent thinking. This was certainly a potential factor in class behavior worth looking at.

Over several other classes, the data was reviewed for this anomaly. In fact, there was a significant trend in the students that far exceeds both the overall population or the subpopulation of engineers. This has potential impact both on how classes are handled and the performance of this group in the work place.

Convergence and Divergence

While this particular instance addresses convergence and divergence as associated with the fourth preference in Myers-Briggs, the specific meaning intended to be critical to this discussion is more in line with the definition below (encyclopedia.com, 2008). This definition is based on the description of the terms by J. P. Guilford.

> "convergence-divergence n. A cognitive style defined by two radically different modes of thinking. At one extreme is convergent thinking, characterized by a tendency to home in on a unique solution to a problem, usually involving the synthesis of information, typified by analytical, deductive thinking in which formal rules are followed, as in arithmetic. It is logical, consciously controlled, reality-oriented, and largely dependent on previously learnt knowledge and skills, and it is measured by conventional IQ tests. At the opposite extreme is divergent thinking, characterized by the fluent production of a variety of novel ideas relevant to the problem in hand. Divergent thinkers prefer, and perform better at, open-ended problems that do not have unique solutions."

This source also continues by relating divergence to creativity. While creativity is certainly of value in the practice of systems engineering, as a minimum, divergent thinking should be considered as looking beyond the given. A basic element of systems engineering should be the ability to expand beyond what is given rather than accept it as the valid outer limit of problem and solution space.

Systems Engineering Course Exercises

The exercise case. The exercises in the classes are fairly complex. The system being addressed is a weather and tsunami warning system for a fictitious island nation (Armstrong, 2003). The location is in the Pacific Ocean at the equator, due south of Los Angeles. The students are given a request for a system of 1,000 fully instrumented weather buoys to be deployed over 4,000,000 square nautical miles of ocean. The purpose is both for weather prediction in shipping lanes leading to the islands and data for research. A tsunami alert capability is also required. A target budget of $250 million for 10 years is also defined.

The problem has many interfaces that must be analyzed and conflicting requirements. The complexities begin with the analysis of the multiple missions in the concept of operations and continue as the students define requirements, develop functional analysis, select an architecture, and complete a system design. Additional issues include a customer provided satellite communications service that will work for weather data, but does not address the critical timing requirements of tsunami warnings. Also, the initial scope of the system with 1,000 buoys exceeds the cost constraints. These problems and more must be addressed with an open mind to challenge the customer data and develop alternative solutions that meet the core needs. Hence, the need exists for divergent thinking.

Impact on Systems Engineering

Systems engineering references. The sources of definition for the expected practices of systems engineering include standards, handbooks, maturity models, and textbooks. A review of EIA 632, IEEE 1220, ISO 15288, the CMMI, and the INCOSE SE Handbook results in similar findings. Although the idea of divergent thinking is implicit in each, there is little that is explicit. The best evidence is in references to identification of relevant stakeholders and an emphasis on multiple alternatives in architectures, technologies, and designs. This also shows in the consideration of multiple alternatives in trade studies. However, the focus in each of them is the convergent path to select and define a single solution. The INCOSE handbook does use the word "creative" in regard to the systems engineering effort, but only in the discussion of the pre-concept phase.

Competencies. Competency models have been developed to more specifically identify the practitioner skills that are needed to perform systems engineering tasks. There are several competency models publicly available and many others that corporations hold close. We can start with the INCOSE Systems Engineering Core Competencies Model (INCOSE, 2005). Most of the competency statements relate to specific tasks that do not rely on divergent thinking. However, in the section on architectural design, the competencies included are "able to generate alternative architectural designs" and "assess a range of architectural solutions" as examples of statements that do.

The National Academy of Public Administration included a systems engineering competency model in an analysis for the FAA (NAPA, 2008). It similarly focuses on typical systems engineering tasks without specific reference to extent of divergence or convergence in performance. There are references that sound divergent such as the plural of designs.

The Systems and Software Consortium's competency model (Wells, 2007) does add some additional features that address how the tasks are carried out more than just the task itself. One such competency is defined as "negative thinking", or the consideration of what is missing. This the part of divergence that is emphasized in this paper, particularly as applied to defining problem space, operational concepts, and requirements.

The need. While most of these sources do not provide obvious statements supporting the need for divergent thinking, they all have more subtle implications. For the various functions of systems engineering to be effective and provide value added, they must expand both problem and solution space beyond what is given to discover what is not given. They must also be performed in an atmosphere that is acceptant of change in direction when the evidence indicates it is necessary. While decisions are necessary and programs cannot be constantly changing direction, being stuck on an original wrong path is also not the right approach. To balance the two extremes in conduct, a balance in the mental approach is also necessary. To do this, the program will be better served by a balance of convergent and divergent thinking rather than one extreme or the other.

Classroom. In a classroom setting, the observed behavior in two groups that were 100% convergent thinkers is a tendency to complete the exercise quickly with the first answer. This limits the effectiveness of complex exercises that are focused on a more in depth analysis and considerations of both method and the answers. For instance, in one exercise the students are asked to consider application of more than one technique such as use case, data flow, or functional flow. Lack of a feeling that other paths should be tried results in only one method being applied. The intended learning about the value of multiple tools in the toolkit does not happen as easily in these groups and must be reinforced by the instructor. Another symptom is the face value acceptance of anything that the customer provides in the problem. In the cases used, there are multiple incorrect facts that the students are expected to challenge. Some examples from the description of the case given above are the satellite communications that will not service the tsunami warning timeline and the request for 1,000 weather buoys which neither fit within the cost constraints nor significantly increase performance. Again, this results in the need for the instructor to stimulate these questions.

Value of Balance

Either extreme in the choice of convergent and divergent thinking can result in problems. A combination of convergence and divergence is depicted in figure 1 (Pugh, 1991). The application is, however, applied after the front end work and specification has been accomplished. The application throughout the systems engineering processes is proposed as a better way to reach an optimal result.

A balance between the two extremes has been shown to produce better results. The following are specific instances encountered in program management and systems engineering training and consulting. In some cases, balance led to effective performance. In others, imbalance became problematic.

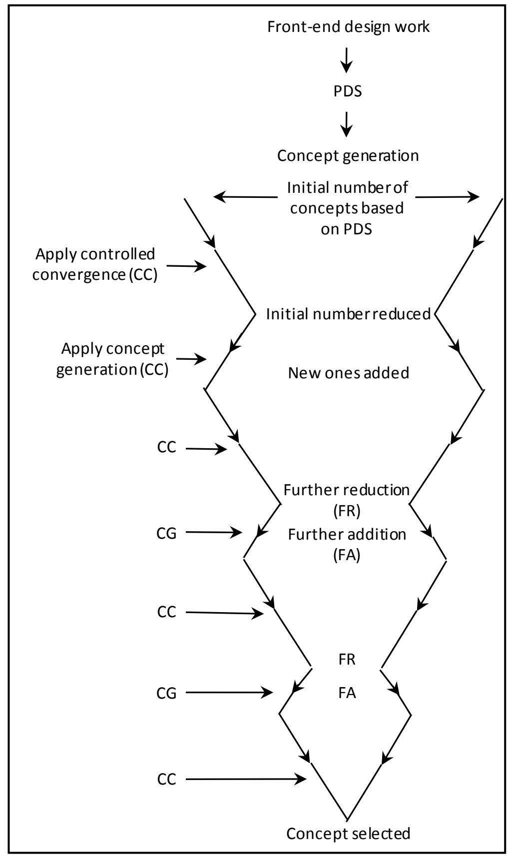

Figure 1 . Combining Convergence and Divergence

Influence on class performance. An example of the impact of the convergence and divergence balance and imbalance occurred during a class exercise at the Defense Systems Management College. Three classes of 30 students were starting the first session of an extended exercise to apply their learning to a simulated major procurement.

One class had a strong convergence tendency in the leadership for this problem. The leaders had made their decisions on the correct path before class started and quickly laid out the plan and handed out assignments. Within 30 minutes, the room was almost empty as the assignees took off on their assigned tasks. There was a lack of buy in and several students felt that they had good suggestions that they had not been given the opportunity to air. The group was headed down the wrong path and had to do considerable rework later.

A second class had leadership dominated by divergent behavior. After six hours the faculty had to intervene. Not only had no decision been made, but the discussion was whether or not the list of possible issues was complete enough. Decision oriented members of this group were growing extremely frustrated.

A third group had a balanced approach. They spent a couple of hours discussing the case and looking at alternatives. Then they selected a course of action and proceeded with an effective approach that the class supported.

Example from a legal case. The following occurred in a contract protest case based on the performance of the contractor in systems engineering. After six months of preparation, the diverger of two investigators of the systems engineering aspects of the case suggested reread the specification. The converger argued for several minutes that it was not necessary since they had read the specification thoroughly several months earlier. When it became apparent that it would be faster to read the document than continue the argument, the converger consented. In doing so, the "smoking gun" jumped off the pages when read in context. Both participants agreed that the balance of their abilities and thinking styles was critical to this and other consulting efforts they worked on.

Convergent/Divergent and the MBTI

Personality. There are multiple approaches to addressing the differences in individual behavior. Some of the more popular are Herrmann Brain Dominance, Kolb Learning Styles, and the Myers-Briggs Type Indicator (MBTI). The MBTI has been used by the author in systems engineering training for 20 years as a means of teaching systems engineers how to work better with people in leading the technical aspect of the program.

The MBTI is based on Carl Jung's analysis of personality. Jung identified three characteristics of individuals that he observed. Meyers and Briggs added a fourth which includes the convergent/divergent dimension. Each preference is described below along with the distribution ratio in the general population and the potential impact of that preference on systems engineering

The first is a preference for introversion (I) or extraversion (E), Figure 2. While we tend to view this as people being outgoing or reclusive, that is only a symptom of the meaning. The actual definition relates to whether a person is energized or drained by either group activity or solitude. The general population is split 50/50 on this preference. The benefits of extraversion in a systems engineer is the comfort level in working with groups on a project. This helps in participation in dealing with multiple stakeholders and team meetings, particularly with Integrated Product Teams. The strength of introversion is the ability to sit down and do analysis without feeling the need to go talk to someone every few minutes. Of course, the weakness of each preference is the lessened ability to do the opposite when the need for that behavior arises.

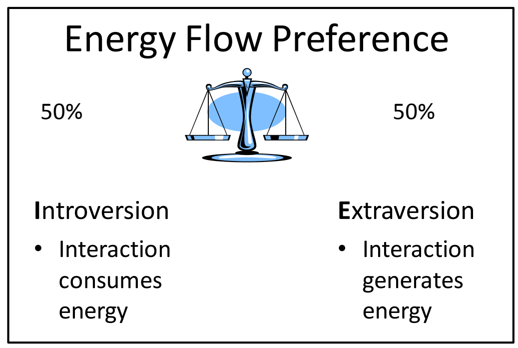

Figure 2. Introversion/Extraversion

The second characteristic addresses the type of input a person is more comfortable receiving. The intuitor (N) has an input preference for concepts and big picture. The sensor (S) prefers hands-on and details, figure 3. The general population is 30% intuitor and 70% sensor. At first glance, the role of systems engineer would appear to favor the intuitor due to the focus on the higher level of abstraction of the system view and the need to be able to deal with more uncertainty. However, big picture concepts that look very good at the surface are too often found not to work when the detail analysis is performed. „This ability to work well with the details of a thorough analysis and interest in getting hands dirty with the actual system as fielded is a systems engineering strength of the sensor.

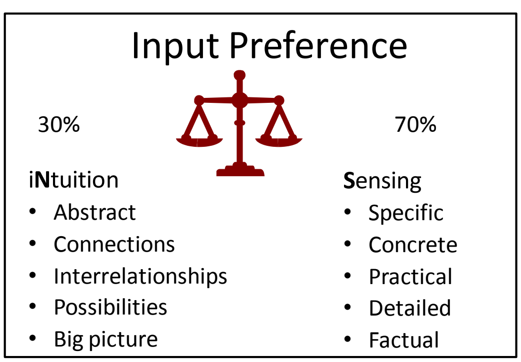

Figure 3. Intuition/Sening

The third is an output preference for the basis of judgment in making decisions. The two options are feeling (F) and thinking (T), Figure 4. The conflict between these two options is the basis for the character Spock in the Star Trek series. He is torn between the emotionally based decisions of his human mother side and the pure logical decisions of his father's Vulcan side. This is the one preference that is gender biased. Males show a preference for thinking by two to one and females prefer feeling by the same margin. However, it must be noted that this bias is far from enough of a difference to form stereotypes or jump to conclusions based on gender. The strength of making logical decisions in systems engineering should be obvious. However, we need to recognize the considerable value in being able to empathize with others in the performance of systems engineering tasks. This is true both in working with the project team and in dealing with the various stakeholders.

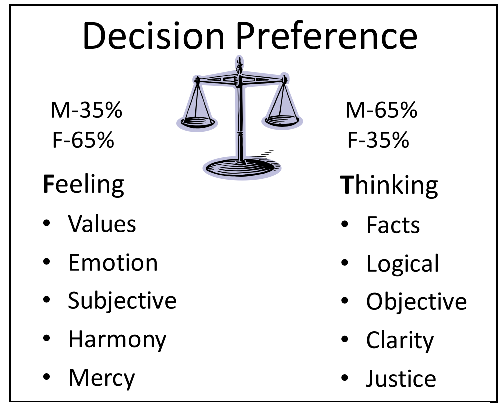

Figure 4, Feeling/ Thinking

The fourth preference added by Myers and Briggs is whether a person is more comfortable with the input side or the output. Those preferring input are perceivers (P) and those preferring output are judgers (J), figure 5. This is the preference that relates to divergent thinking or convergent thinking. In the extremes, a perceiver never comes to a conclusion and the answer to every question is three more questions. This behavior is associated with laboratory scientists. At the other end of the spectrum is the total judger who has an answer before the question is even asked. A significantly high percentage of project managers exhibit this preference. In the general population, there is a slightly higher percentage of judgers than perceivers. This is the area in which an exceptional distribution was noticed in the students observed and is the focus of this analysis. The strength of the judging preference is the ability to make the decisions needed to execute the program in a timely fashion and not keep the rest of the technical team waiting for the decisions to be completed. The weakness is a tendency to rush to judgment and not look at enough alternatives. A particularly significant statement is made by (Kroeger, 1988) in discussing the judger, "Judgers, in contrast, have the tendency to judge – rather than to respond to new information, even (or perhaps especially) if that information might change their decision." This tendency can be very dangerous in complex systems development. The value of the perceiver preference is the ability to identify multiple alternatives or issues that others have not recognized for consideration. The weakness is the lack of getting to a decision on time.

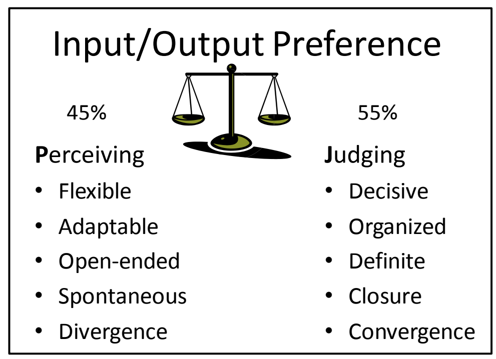

Figure 5. Perceptoin/Judgment

The resulting four preference choices are Extraversion/Introversion, iNtuitor/Sensor, Feeling/Thinking, and Perception/Judgment. When each of the preferences is determined, the result is a four letter preference type. The set of 16 combinations result in the 16 Myers-Briggs types. These are intended to be helpful in understanding differences in normal behavior and are not related to quality of performance or identification of psychological problems. The 16 types and the average percentage found in the general population are shown in figure 6.

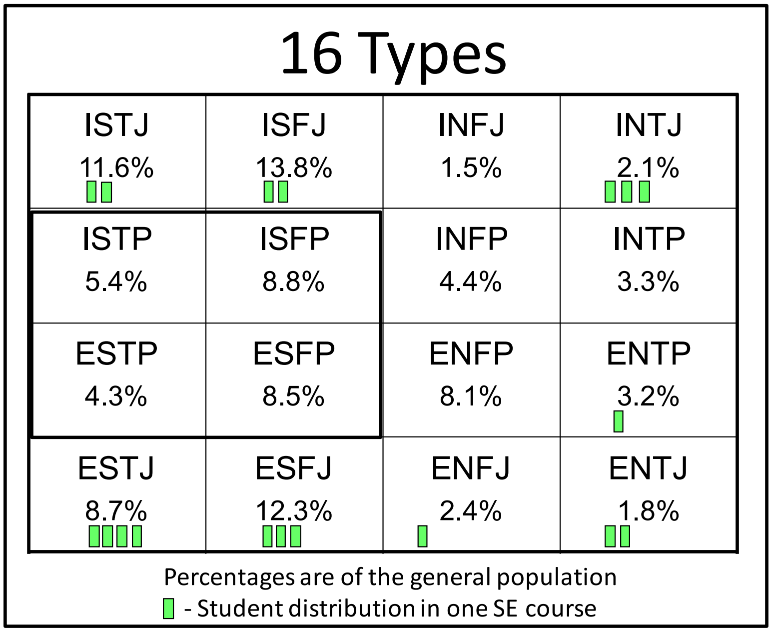

Figure 1. Introversion/Extraversion

Figure 6: The 16 Types

The Data

The data from 109 students in a series of classes is shown in Table 1. The percentages for each preference, as compared to the general population as follows:

Preference	SE Students	General Population	Preference	SE Students	General Population
Extraversion	53	50%	Introversion	56	50%
iNtuition	66	30%	Sensing	43	70%
Feeling	37		Thinking	72	
Perception	13	45%	Judgment	96	55%

Table 1. Class Preferences and General Population

The general population numbers for Feeling and Thinking are not included. As described above, this preference has a gender bias and the gender data for the classes was not retained. However, the numbers are consistent with a predominantly male population which is consistent with the overall class population.

The predominance of judgers is considerably removed from the general population. Engineers generally tend to lean towards the judgment preference. Table 2 shows the preferences for several categories of engineers and engineers in general based on early MBTI scoring returned to the Center for Application of Psychological Type (Briggs. 1988). The group of students that is the basis of this analysis has a considerably higher percentage of judgers than even the highest group, chemical engineers.

Type of Engineer	% Judgment	% Perception	Number
Chemical	78.55	21.15	52
Electrical and Electronic	62.96	37.04	54
Mechanical	62.34	37.66	77
Engineer	60.45	39.55	986
Aeronautical	53.70	46.30	54
Mining	44.21	55.79	190

Table 2. Judgment/Perception Preference of Engineers

One factor that may play in the classroom situation is the group of personality types that exhibit both sensor and perceiver preferences, xSxP, as indicated by the dark border in the middle left of figure 6 above. These are described (Kroeger) as people who prefer to learn by hands-on rather than classroom. They also are less likely to be interested in what would be perceived as a theoretical discussion. The absence of this group in significant numbers will have an influence on classroom behavior but may be a compensating factor in the workplace. However, even doubling the number of perceivers in the classes would not explain the shortage experienced.

Convergence/Divergence. While there are many other personality descriptions in use, Myers-Briggs is one that both addresses the idea of convergence and divergence and is commonly used by many organizations which means data is available to take advantage of if there is interest in looking to see if this condition exists. The Herrmann Brain Dominance Indicator, figure 7, has several concepts that are similar to the MBTI and Jung's theories. However, it lacks the dimension addressed in the perception/judgment preference. Kolb's learning styles has some of the concepts but they are not as clearly identifiable and separable for the purpose addressed here.

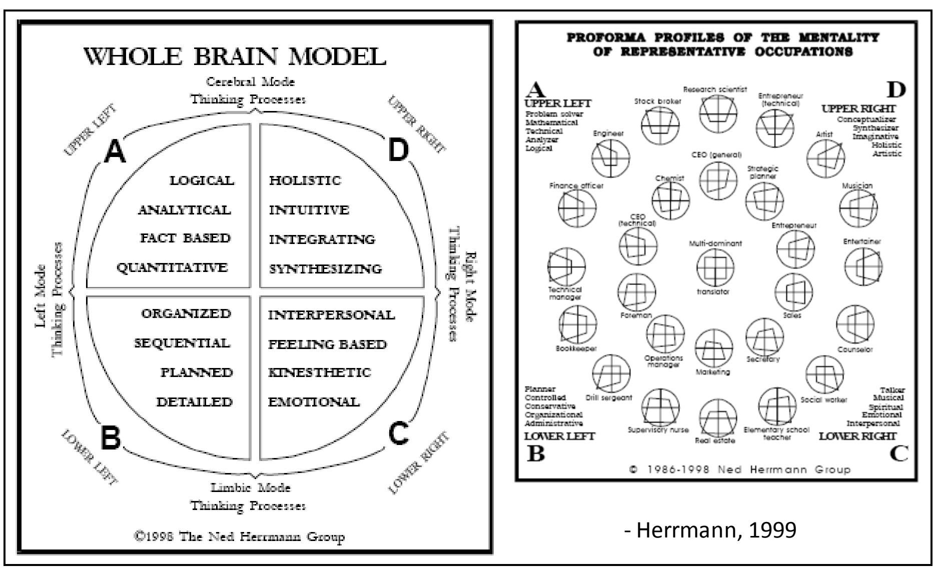

Figure 7. Herrmann Brain Dominance

Several other approaches that address personality are focused on defining abnormal or problematic conditions. These include the Minnesota Multiphasic Personality Indicator and the Personality Assessment Indicator. The latter addresses the characteristics in figure 8. Although these are more enthusiastically supported by the community of psychologists, they are not applicable to the situation being analyzed

- **Clinical Scales**
- Somatic Complaints
- Anxiety
- Anxiety-Related Disorders
- Depression
- Mania
- Paranoia
- Schizophrenia
- Borderline Features
- Antisocial Features
- Alcohol Problems
- Drug Problems

- **Interpersonal Scales**
- Dominance
- Warmth

- **Treatment Scales**
- Aggression
- Suicidal Ideation
- Stress
- Nonsupport
- Treatment Rejection

- **Validity Scales**
- Infrequency
- Negative Impression
- Positive Impression
- Inconsistency

Figure 8. Personality Assessment Indicator Scales

Other Potential Areas of Concern

While the focus of this discussion has been the distribution of divergent and convergent thinkers in the systems engineering population, there are other potential preferences to address. For instance, the distribution of big picture (intuition) and detail (sensing) thinking was significantly tilted towards the big picture side in this sample population. At first look, it would seem appropriate that systems engineers have this tendency since the primary value in systems engineering is to coordinate the detail views of specialist in multiple disciplines to achieve the higher order purpose. However, extremes can have negative consequences even when they appear to be the right extremes.

In one small software development organization, the manager was having difficulty in promoting from within for first level managers. A sample of 30 of the employees, about 15% of the organization, taking part in a class was 85% introverted, sensing, thinking, perceivers (ISTP). This type is only about 5% of the general population. However, the characteristics are positive for software developers. They are comfortable working at a computer station developing detailed logic and coming up with creative solutions to the technically challenging problems this particular group faced. However, when they moved to take on management responsibilities, they needed to get away from their own screen and interact with those they managed, see the big picture, deal well with people, and make decisions. It is not a case of not being able to do these tasks, but rather needing to understand that they were out of the comfort zones of most of the employees. Special care needed to be taken to aid in the transition. Knowledge of the situation would allow management to address the previously unrecognized issues and more effectively develop the leaders they needed.

Conclusion

The initial observations of a bias towards convergent thinking in a student population have potential impact on both the teaching and practice of systems engineering. If this holds to be true in the general population of the systems engineering community, the result is likely to be a less effective definition of both problem and solution space and a much less than optimal end product. Awareness of the circumstance can lead to corrective actions. A balance should be sought in the use of both styles of thinking. Where practical, this can be established by understanding the strengths of potential systems engineering practitioners and assuring that both styles are represented. Should the situation exist, as has been seen in some cases documented here, extra effort needs to be applied to stimulate additional divergence. However, this is not an easy task, particularly when attempted by someone who is a strong convergent thinker. Further research into the validity of the observations, extent of the condition, impact, and mitigations is warranted.

References

Armstrong and Bocast, *The Integration of Systems Engineering and Software Development*, Software Productivity Consortium, April 2003

Bennet, E. A., What Jung Really Said, Schockten Books, New York, 1983

Capability Maturity Model Integrated, Development, Version 1.2, Carnegie Mellon University, August, 2006

EIA 632, *Process for Engineering a System*, Electronic Industries Alliance, Arlington, VA, January 1999

Herrmann, *The Theory Behind the HBDI® and Whole Brain® Technology,* August 1999

http://www.encyclopedia.com/doc/1O87-convergencedivergence.html

IEEE 1220, *Standard for Application and Management of the Systems Engineering Process,* IEEE, 345 East 47th Street, New York, NY 10017, 1999

INCOSE, *Systems Engineering Handbook, a Guide for System Life Cycle Processes and Activities, June 2006*

INCOSE UK Advisory Board, Systems Engineering Core Competencies, 31 May, 2005

ISO/IEC 15288, *Systems engineering – System life cycle processes*, ISO, 1 rue de Varembe, CH-1211 Geneva 20, Switzerland, 2002

Kroeger and Thuesen, *Type Talk,* Delecorte Press, New York, 1988

MIL-STD-499B, *Systems Engineering*, May 1, 1995

Myers and McCaulley, *Manual: A Guide to the Development and Use of the Meyers-Brigs Type Indicator,* Consulting Psychology Press, Palo Alto, CA, 1988

Naval Systems Engineering Guide, 2004

National Academy of Public Administration, Identifying the Workforce to Respond to a National Imperative ….The Next Generation Air Transportation System (NextGen), 2008

Pugh, Stuart, *Total Design: Integrated Methods for Successful Product Engineering,* Addison-Wesley Publishing Company, Wokingham England, 1991

Wells, Systems Engineering Competency Model, Systems and Software Consortium, Inc, 2006

BIOGRAPHY

Jim Armstrong has practiced systems engineering for 40 years, performing various roles including configuration management, test, deployment, chief engineer, program manager, and program element monitor. For the last 20 years, he taught, consulted, and appraised systems engineering in industry and government. Also, he was on the author teams for several of the standards and models discussed in this paper. He is also certified in the use of the Meyers-Briggs Type Indicator.