Collaborative Systems Thinking: A response to the problems faced by Systems Engineering's "middle tier"

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Abstract. Experienced systems engineers are adept at more than implementing systems engineering processes: they utilize systems thinking to solve complex engineering problems. Within the space industry demographics and economic pressures are reducing the number of experienced systems engineers that will be available in the future. Collaborative systems thinking within systems engineering teams is proposed as a way to integrate systems engineers of various experience levels to handle complex systems engineering challenges. This paper uses the GOES-R Program Systems Engineering team to illustrate the enablers and barriers to team level systems thinking and to identify ways in which performance could be improved. Ways NASA could expand its engineering training to promote team-level systems thinking are proposed.

Introduction: What is Collaborative Systems Thinking?

Systems Thinking: Broadly defined, systems thinking is a way of thinking about the whole: a system and its context. While many definitions exist for systems thinking, the common themes across these definitions are complexity, interrelationships (interfaces), context, emergence, and holism. Definitions specific to engineering focus on the use of tools and experience to consider the technical and social component and interactions of a system (Davidz 2006) and associated systems thinking with problem solving and brainstorming activities (Jansma and Jones 2006).

Systems thinking is a skill leveraged to avoid potential future problems. Systems thinking skills include understanding dynamic system behavior, identifying feedback processes, finding and explaining patterns of system behavior, and identifying ways in which to influence that behavior (Richmond 1993, Sweeney and Sterman 2000). Such skills are useful in understanding the limitations of systems models, interpreting and influencing non-linear processes, and recognizing time delays between systems inputs and outputs (Sweeney and Sterman 2000).

Within engineering, systems thinking development is enabled by experience, individual characteristics (e.g. curiosity and a tolerance for uncertainty), and a work environment that supports the development of systems skills (Davidz 2006). For a more detailed discussion of systems thinking definitions and development, see (Davidz 2006) and (Lamb and Rhodes 2008).

Defining Collaborative Systems Thinking: Inputs from literature and a set of interviews (see Lamb and Rhodes 2009) were used to form a definition of collaborative systems thinking. In addition to the common system thinking definition themes, literature on team thinking and memory emphasized the role of team interactions, or transactions, in forming both a shared understanding of the systems and pointers to specialized knowledge and experience within a team (Salas and Fiore 2004, Wegner 1986). Also found in the literature was demonstration of the importance of diversity in thinking styles (e.g. divergent, convergent) as important for the design process (Stempfle and Badke-Schaub 2002). Further literature highlighted the importance of communicating technical information using multiple communication media (e.g. sketches, questions, models) (Dym et al 2005).

Interviews with senior systems engineers and program managers within the aerospace industry revealed phrases such as 'holistic approach,' 'understand the problem, 'keeping a systems view', and 'teasing out interconnectedness.' These interviews also introduced the concepts of producing a final product, managing interactions among multiple functions, using multiple and high-bandwidth forms of communication (e.g. face-to-face), the importance of a creative and supportive environment, the use of standard design process to manage design knowledge, being aware of other teams' members, and the need for leadership recognition and support of systems thinking.

By integrating these inputs, the following definition of collaborative systems thinking was derived:

> Collaborative systems thinking is *"an emergent behavior of teams resulting from the interactions of team members and utilizing a variety of thinking styles, design processes, tools, and communication media to consider the system, its components, interrelationships, context and dynamics toward executing systems design."* (Lamb and Rhodes 2008)

This definition captures the primary difference between individual and team systems thinking: the concept of team thinking, or the group processing of information including recall and interpretation. Given the importance of experience in developing systems thinking and the reduced opportunities to gain such experience, teams offer an opportunity to pool systems experience into one working unit. Focusing on the team level also emphasizes creating a supportive environment for systems thinking expression and development. Such an environment facilitates the exchange of knowledge from experienced engineers to younger engineers in the forms of hands-on mentoring, parables, and shared references. In such a context, not only will younger engineers be exposed to systems thinking, they will be learning from a wide base of experience to which they might otherwise not have access.

The Challenge: An aging workforce threatens systems thinking resources

If experience is critical for systems thinking development, it is logical that experienced engineers are more proficient systems thinkers. Inidividuals with 30+ years of program experiene comprise 40% of the aerospace workforce. Many of these individuals are currently eligible for retirement:

65% of these most experienced workers will be eligible for retirement by 2014. At the same time lesser experienced engineers are finding fewer opportunities to gain the experiential learning critical to systems thinking development.

Engineering Demographics: Twenty-five percent of the aerospace industry will be eligible for retirement by 2011 according to (Black et al 2006). This 25% represents the engineers with the greatest depth and breadth of program experience: the individuals who have been most enabled to develop systems thinking. Figure 1 shows that the Goddard Space Flight Center (GSFC) science and engineering workforce is slightly older than the overall Aerospace workforce, and much older than the entire US workforce. In terms of retirement eligibility, 17% of the GSFC science and engineering workforce is currently eligible for retirement and 30% of the current workforce will be eligible for retirement within the next five years.

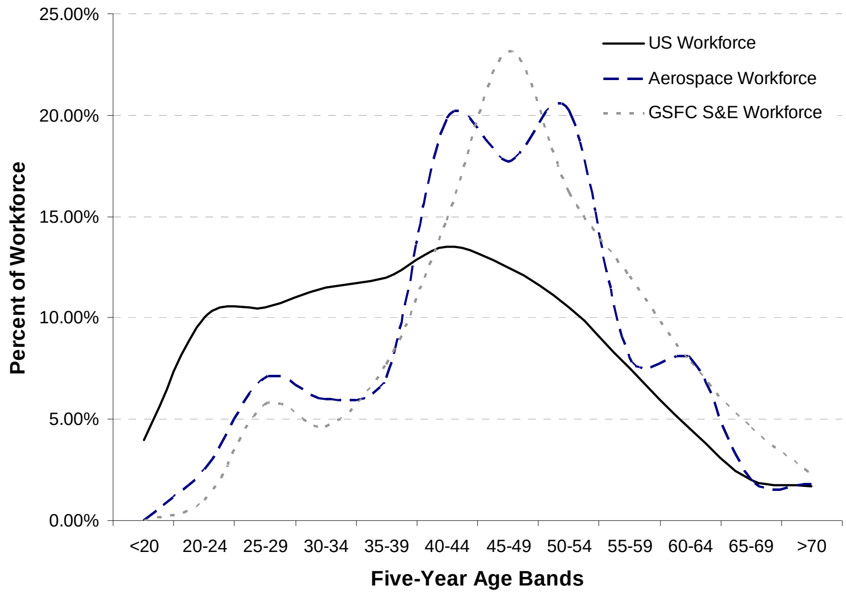

Figure 1:GSFC, Aerospace, and US Workforce Demographics adapted from NASA Workforce Information Cubes and (Black et al 2006)

Program Opportunities: An aging workforce is not itself necessarily a cause for concern. However, there are fewer new large programs and these programs have longer lifecycles than their predecessor programs. Therefore, younger engineers will not have the same quantity of career systems experiences as engineers more advanced in their careers. Because systems thinking development is linked to systems experience (Davidz 2006), fewer programs mean fewer opportunities to develop systems thinking skills. Engineers who entered the industry in the 1960s had the opportunity to work on six different manned space flight programs over a 40 year career. An engineer entering the industry in the mid-1980s has had experience with only one or two manned space flight programs. As NASA ramps up the Constellation program, many of the younger engineers on the program will have no manned space flight program development experience. Without opportunities to develop systems thinking, these engineers are more likely to relearn lessons of the past by repeating old mistakes on new programs.

Good Systems Engineering Processes Can Help: The goal of processes within systems engineering is to address problems across the system's lifecycle in a systematic way. One of the objectives of engineering process standardization is the accurate prediction of cost, schedule, and performance. Engineers are the most variable component of the design process (Martin and Davidz 2007). Introducing standard ways of executing tasks helps to reduce this variability and facilitate scheduling and cost estimating, and enable the overall effectiveness of the engineering effort. Standards support engineering excellence by saving engineers from ‘reinventing the wheel’ and preserving efforts for true innovation (Gill and Vaughan 2006). Standard processes capture good systems engineering practices and help to ensure interfaces and requirements are properly managed. Standard processes and best practices are based on lessons of the past (So and Andary 2007).

But, Processes are Not Enough: Even the best process, though, cannot take a bad program and make it good. Rather, good processes when appropriately followed keep a good program on track. Leadership and the "art" of systems engineering are the additional needed components for success (Ryschkewitsch 2008). While systems engineering deals with requirements and interfaces, creating these are not the end goal. Finding the right design is the end goal of systems engineering (Griffin 2007). This pursuit is aided by process, but also requires the systems engineer to act as the link between the art and science of engineering; bridging the gap between design and analysis. Whereas analysis is conducive to rules and processes, the art of system engineering is learned through experience and incorporates systems thinking, the ability to know when and where to probe a design.

Addressing the Challenge: Collaborative Systems Thinking

Through 10 full and 17 abbreviated case studies, a set of collaborative systems thinking team traits were identified. The methodology used and the results are discussed in more detail in (Lamb and Rhodes 2009). Below is a brief discussion of identified collaborative systems thinking team traits.

Generalized Traits of Collaborative Systems Thinking Teams: Three generalized traits of collaborative systems thinking (CST) teams are that these teams have comparatively more program experience, inclusive cultures and consistent team structures. In the discussion below, collaborative systems thinking ability is a triangulated measure based on inputs from team members and third-party assessments of team performance.

Team experience is an indicator of CST. Both years of experience and number of past similar program experiences were correlated to team CST. Because individuals on teams represented a wide range of experience (4-40 years and 0-15 past programs on some teams), the mode of each team was used as most representative of the average team member's experience. By this metric, years of experience and team collaborative systems thinking are correlated with a coefficient of 0.63. The number of past programs worked is a better predictor of CST, with a correlation coefficient of 0.86. Because systems skills are based on an understanding or appreciation of the entire system, it is logical that the number of systems worked is a better indicator of systems thinking. This observation reinforces the value of internal research and development (IR&D) programs that provide opportunities for early career hires to participate in multiple programs and program lifecycle phases, thus providing the necessary systems experience to foster strong CST teams.

A team's culture is also an important indicator of its CST ability. CST teams have cultures of inclusion; these are teams in which individuals have a sense of participation. One measure of this participation is decision making. Team members were asked to rank the relative frequency of individual decisions versus consensus decisions. The rate of team, or consensus, decision making has a strong correlation (C=0.70) with team reported collaborative systems thinking ability. Another indication of CST team culture showed up in team communication preferences. CST teams were more likely to describe their teams as having open communication based on face-to-face communication. These teams describe themselves as more creative and were more likely to use sketches, prototypes, and models to communicate technical ideas.

CST Team Structure: One consistent difference between teams with high and low ratings of collaborative systems thinking was team structure. The structure observed consists of three tiers of team membership: systems leadership, an intermediary, or 'middle' tier of developing systems professionals with functional backgrounds, and functional experts. This structure, observed through organizational charts or discerned through conversation with team members, was observed in each of the six full case studies with high rankings for collaborative systems thinking. One or more tier was absent in those case studies with lower ratings of CST. The pattern was also reinforced through the abbreviated case studies, in which individuals described the structural traits of high and low CST teams on which they had participated.

The systems thinking leadership of a team is composed of one or more individuals, all strong individual systems thinkers, who balance both the technical and social interactions of the team. These individuals guide their team, adjusting their interaction style to best serve their purpose and audience. They excel at communicating at multiple levels of abstractions and multiple levels of system detail. These traits align with those of the 'highly regarded' systems engineers characterized in (Derro 2008). These traits, developed from a study of effective systems engineers at NASA, include the ability to influence others, strong communication skills, engaging in mentoring, critical thinking, risk management, and the ability to lead others to new insight using analogy and insightful questioning.

The middle tier of developing systems professionals consists of individuals with functional responsibilities (e.g. subsystems leads or representatives of different functions) who interact closely and have an appreciation for systems issues. These individuals act as an interface between the functional experts and the systems leadership. The middle tier excels at presenting detailed technical information, tailoring the presentation to their audience and facilitating decision making. By nature of their role within the team, these individuals are well poised to develop strong systems skills.

The functional experts bring specialized technical knowledge to the team. These individuals are less involved in the day-to-day interactions and decision making of any single team, as they often contribute to several teams simultaneously. As such, the functional experts are less aware of systems issues and the greater systems picture.

A team lacking any one of these tiers suffers from a lack of leadership and/or a failure to process and share the information necessary to support decision making.

CASE STUDY: GOES-R

What is GOES-R? The National Oceanic and Atmospheric Administration (NOAA) operates a system of Geostationary Operational Environmental Satellites (GOES) to provide continuous weather imagery and monitoring of meteorological and space environment data to protect life and property across the United States. One of NOAA's principal missions is to provide forecasts and warnings for the United States, its territories, adjacent waters and ocean area for the protection of life and property and enhancement of the national economy. This mission requires the capability to acquire, process, and disseminate environmental data on an extensive spatial range (global, regional and local) on a variety of time scales. Two GOES satellites remain operational at all times providing coverage for the eastern United States and most of the Atlantic Ocean and the western United States and Pacific Ocean basin. GOES satellites provide critical atmospheric, oceanic, climatic and space weather products supporting weather forecasting and warnings, climatologic analysis and prediction, ecosystems management, and safe and efficient public and private transportation. The GOES satellites also provide a platform for solar and space environmental observations.

The GOES program currently consists of three series of satellites—identified by letters during development, and numerically post-launch. The GOES-I/M series (8-12) is the current operational series. Transition to the GOES-N/P series has commenced with the successful launch of GOES-13 in 2006. The GOES-I/M and –N/P series share the same generation primary instrument payload. The GOES-R series is a $7 billion system of satellites, sensors and data processing and distribution, which represents a generational change in both spacecraft and instrument capability, with initial launch capability in 2015. It will provide the first major improvement in instrument technology since GOES-I was launched in 1994. The GOES-R series will introduce other new technologies in both the Space and Ground Segments. These advances will improve the nation's ability to monitor and forecast weather and environmental phenomena with a significant increase in the number of products.

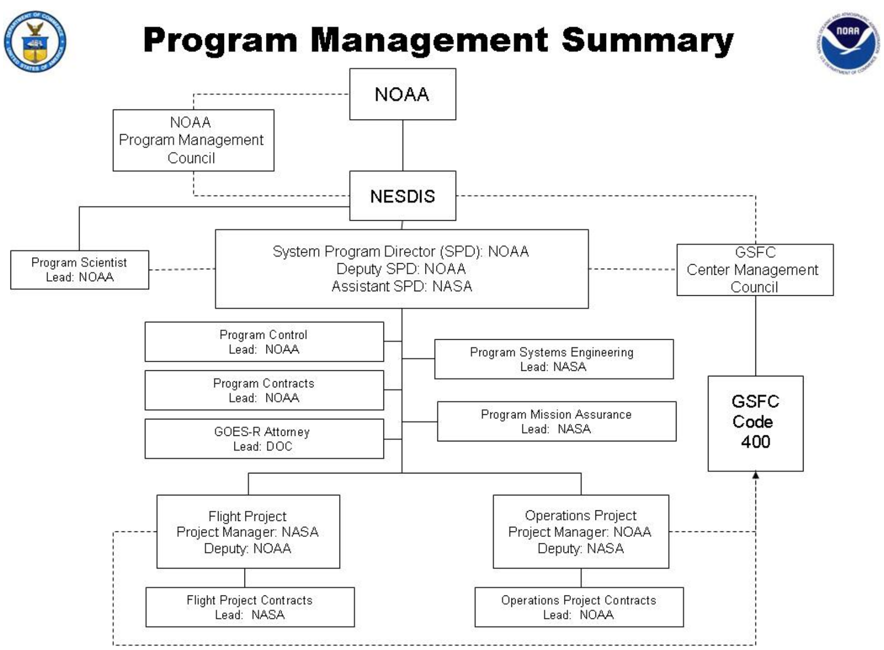

Figure 2: Diagram of GOES-R Program Structure

GOES-R Program Structure. GOES-R is a collaborative development and acquisition effort between NOAA and the National Aeronautics and Space Administration (NASA). Program activities occur at the co-located Program and Project Offices at Goddard Space Flight Center. The GOES-R program acquisition and management strategy was restructured at the end of the Formulation Phase from a single-system prime NOAA contract acquisition to an inter-agency dual-contract acquisition for the Acquisition and Operations Phase of the Program. Under a dual-contract acquisition strategy, NASA is procuring the Space Segment and NOAA is procuring the Ground Segment. A Program Systems Engineering Team was created to ensure the overall system engineering and integration is accomplished. This group is responsible for end-to-end systems requirements definition, design, integration, planning, coordination, and adjudication of the space and ground segments. One of the group's challenges is to tailor procedures to apply to the GOES-R program to meet the unique demands of this joint inter-agency acquisition -- safeguarding NOAA's oversight of the GOES-R program while also safeguarding NASA's effective exercise of its expertise over the Flight Project. Another challenge is to identify and remediate inconsistencies between the designs, schedules and test plans of the two projects as early as possible in the program when they are less costly to fix. The Program Systems Engineering

Team (PSE) is central to integrating the strengths of two agencies to create the best system possible.

GOES-R Program Systems Engineering (PSE). The PSE consists of approximately 20 systems engineers with a wide range of backgrounds – software, mechanical and electrical engineering as well as meteorology and project management. Rather than focusing on instrument or satellite subsystems, individuals focus on general programmatic themes –system design, integration, testing, configuration control, requirements tracking and flow, image navigation and registration, instrument processing algorithms, and science product algorithms. There is considerable overlap among these themes, requiring team members to work collaboratively. The team lead is a NASA systems engineer and the deputy is a NOAA systems engineer. The rest of the team is a collection of NASA and NOAA civil servants and contractors from several companies on several support contracts. Team members are chosen primarily by the expertise they bring to the group, rather than based on their corporate affiliation. The PSE team chose to participate in this study in order to gain insights into its strengths and weakness in the area of CST with the goal of improving. High CST ability is crucial to the success of this team and due to its critical program integration role, to the success of the entire $7 billion program. A discussion of how well this team embodies the three traits of collaborative systems thinking follows.

The first trait is program experience. The GOES-R PSE team members have comparatively fewer past program experiences as compared to other teams in the study. On average, NASA and NOAA have large programs with long lifecycles – the GOES program has been in existence for decades, so this finding is expected. Team members have more experience in the current program or a small number of other programs, but lack the perspective and breadth of knowledge gained from supporting multiple programs.

The second trait is an inclusive culture. PSE's survey results had the most positive responses to the question about trusting each others' abilities to meet deadlines and about average responses to the question about respecting other team members' technical abilities. The answers suggest that trust and respect are well in place. However, PSE is a team composed of individuals from multiple cultures. This is a strength due to the different skill sets that are brought together into this team, but can make it harder for this team to form a consensus around values and goals. This showed up in the responses on decision making that were evenly distributed between 'consensus' and 'individual' decision making. On the survey question "Does this team have a clear goal" this team's score was significantly lower than other teams in the survey. People agreed on why the team existed, but not what the team is doing. This is understandable given that most team members are new to the team. Most were project system engineers in the past and are grappling with the differences between project and program systems engineering. A similar pattern is observed for the question "Does this team engage in critical discussion of new ideas." This shows that procedural issues like how decisions are made are not uniformly perceived. The PSE team is the 'newest' of the teams in the study. Most members (10/19 surveyed) have been with PSE for a year or less. The weaknesses identified in the survey are not surprising given the relative newness of the team, and are certainly correctable with time. The multiple cultures aspect is and always will be a challenge: PSE has representatives of three organizations (plus contractors). There's no consistent incentive for everyone on the team (especially from a contractual standpoint—for the contractors). But this model increasingly reflects reality—especially with the prevalence of engineers retiring and returning as contract workers.

As with most of the teams involved in the case studies, a portion of the PSE team is geographically separated from the main body of the team and relies heavily on teleconferencing and email.

These individuals have more difficulties engaging in discussion and feeling a part of the team. Collaboration across distributed situations is slowed by phones that only allow one side to talk at a time. It's these really small points that can interrupt the cohesiveness of a team. For PSE, communicating in less than optimal conditions is an ongoing challenge. When a conversation is really critical the geographically dispersed team members are invited to fly down to participate with the team directly.

The third trait is the three tier structure described above. Considering the PSE as a team, you have the dual NASA/NOAA leadership and middle tier (remainder of PSE). The third tier is composed of the functional experts in the Ground Segment Project and Flight Project teams, who are actually not a part of the PSE team. The interviews suggested this is an 'us' and 'them' type situation where those contributing the detailed information come from the ground and flight systems groups having team cultures distinct from PSE and different from each other (ground more aligned with NOAA, flight more aligned with NASA).

Key Challenges of the Middle Tier. In this case study, there are several challenges facing the Middle Tier. The first is to make up for the lack of breadth of program experience that is the reality for most of the team. There are several ways to do this that are in fact already being done: using the senior systems engineer who has that experience as a mentor and consultant, providing resources (books, online databases, other engineers at Goddard) so that the engineers get the data they lack, and to allow more time for tasks so that this data gathering process can happen. Training and rotation programs are also a logical solution to this challenge.

The PSE's next challenge is developing a common understanding, or big picture, of the GOES-R program. Members of PSE must understand the political drivers, the goals, the stakeholders, the various system components, and the history for the GOES program. Comparisons to the previous GOES Programs can lead to erroneous conclusions because the instruments for GOES-R have improvements over the previous instruments, deliver different data products, and require different operational processes. Comparison to previous NASA missions can lead to erroneous conclusions because NOAA stakeholder interests are not necessarily represented by past NASA missions. The GOES-R goal is to blend NASA innovation in a framework of NOAA continuity.

Developing a unified culture within the PSE is the next challenge. The whole team must understand the decision making process, other team processes and the team deliverables. Semantics can be a barrier to this effort. A 2007 study of barrier and enablers to systems thinking at GSFC, showed that even within the GSFC community, there were diverse definitions for systems thinking. The divergence in definitions is linked to confusion over how leadership expected systems thinking to be demonstrated in the workplace. Other challenges seen to developing systems thinking include intangibles such as organizational culture and individual attitudes.

The final challenge is to get members of PSE's middle tier and the discipline engineers better integrated. The key here is for all to recognize that they share a common goal – the success of the mission. It is also important for engineers on both sides to value the contributions of the other side to this success. This can be fostered with more face to face contact, and joint participation in engineering activities. Comments and data from other case studies suggest that the functional experts should be held tightest during detailed design when their inputs are required frequently for system-level issues. The goal needs to be to get people interacting more like one big team at the technical level.

In summary, the PSE team's responses to a survey and interview support illuminate barriers unique to team-level systems thinking development.

- Barriers to team-level systems thinking included the existence of several subcultures within PSE (NOAA is more operational, NASA is more engineering, contractors are specialists). These differences showed up in differing perceptions about team decision making—which is split along organizational lines.
- The team operates in a distributed environment. Team interactions are inhibited by collaboration technology (e.g. conference calls). The medium for interaction limits the quality of conversation in which the team engages. This and other barriers to distributed collaboration are discussed in (Utter 2007).
- Reinforcing the confusion expressed by junior systems engineers in the 2007 study, the group relies on informal communication and coordination. While informal communication (e.g. water cooler conversations) has proven consistently important across companies and case studies, this results in some confusion about process and documentation flow within the middle tier. Such confusion is a particular problem within PSE because of the integration of NOAA and NASA systems engineering process.

Responding to the Challenge

What is Goddard doing to address the middle tier? NASA and Goddard systems engineering organizations are aware of the challenges faced by engineers in the middle tier and have taken steps to address them.

Several NASA Centers have hands-on systems engineering development programs including: Glenn Research Center (GRC), GSFC, Jet Propulsion Lab (JPL), and Ames Research Center (ARC). In addition to these Center programs, the NASA Office of Chief Engineer in 2008 has been given the responsibility for implementing an effective systems engineering program and strategy across NASA. The program Systems Engineering Leadership Development Program (SELDP) is being developed to identify and develop the next set of "highly regarded" systems engineers within NASA. The SELDP program leverages existing systems engineering training programs within the centers such as Systems Engineering Education Development (SEED) at GSFC and Space Mission Excellence Program (SMEP) at the GRC. It also leverages existing NASA Academy of Program/Project & Engineering Leadership (APPEL) programs and courses for leadership training and workshops.

At Goddard, four fundamental elements critical to developing the middle tier have been identified: mentoring by Systems Leaders, on the job training including rotational assignments, a curriculum of technical courses, and systems leadership training. The Goddard SEED Program is designed to develop the middle tier systems engineers into fully qualified systems engineers over a two to three-year period. (SEED 2006). Assignments and classes are selected to broaden the participant's experience across several disciplines, subsystems, and phases of the mission life cycle. The SEED Program maintains at least six participants at any given time with at least three new candidates per year. Since SEED was created in 2002, nine engineers have graduated from the program and four engineers are in the current class. A new class is scheduled to be formed at the end of this year.

Both the SELDP and the SEED Programs recently adapted a selection process that ensures the selection of the high potential participants. Participant selection does not only focus on identifying individuals who have proven technical/discipline capability, but also those who have demonstrated key systems engineering leadership capabilities and behaviors. Leadership elements include the ability to use critical and systems thinking and judgment, and the ability to make effective decisions for large, complex system and out-of-the-box thinking. Nominees who were highly ranked were interviewed to determine if they exhibited the systems engineering leadership behaviors and aptitudes necessary to become an expert in the field. Systems engineering leadership behaviors have been identified in studies conducted at Goddard and JPL (Jansma and Jones 2006). Currently additional expert systems engineers at other Centers have been interviewed to validate these behaviors and aptitudes.

Future Work and Conclusions

What programs or changes could Goddard initiate? The following four areas are candidates for enhancing existing education courses:

1. Educate engineers to think more deeply about systems in their context or environment. This should include improving the ability to understand system boundaries, and how these may shift over time. Engineers need to be educated to understand how systems react to internal/external impacts. This includes developing knowledge of constructs for impact analysis and methods decision making. It should include a common "big picture" understanding of the system.
2. Develop the 'situational leadership' abilities of engineers in regard to how to make decisions at multiple levels – component, system, system of systems (Rhodes et al, 2008). This includes an improved understanding of the decisional trade off process for local versus global system value delivery. This should include considering the frame of reference of the engineers in various organizations and in the different tiers, and developing the understanding that people make decisions based on individual perceptions.
3. Provide more education and experiential learning opportunities in regard to 'systems in time'. This includes how to think about systems and system interactions within and across life cycle phases. Also important is the ability to anticipate future scenarios, and how system decisions in present time may enable flexibility for the future.
4. Recognizing the benefits of Collaborative Systems Thinking, develop training for entire teams, contractors and civil servants – teams such as the GOES-R PSE team. This could be one of the three suggestions above, or a different topic, so long as the whole team is participating together.

One initiative that may benefit the middle tier systems engineers is to establish "focus groups" within the Engineering Directorate. These are small groups of 4 – 7 systems engineers working on areas with a common theme. For example, we can create a focus group for the Earth Science ground system engineering and a focus group for spacecraft systems engineering, etc. The primary purpose of these focus groups is to improve the systems engineering capabilities through knowledge sharing and problem solving among the group members. Additionally, they provide a measurement and feedback on how well the systems engineering processes were being applied on the various projects. They are non-confrontational assessments of the issues, successes and the challenges that were being faced each day by the systems engineers in the field. It may also be an excellent way to monitor the inner workings of the systems engineering processes without a formal assessment. People tend to be nervous about formal surveys and assessments and they will often hold back information or exaggerate performance under the scrutiny of such formality. On the other hand focus groups are less formal and less confrontational and engineers are more willing to open up on what the real issues are.

Goddard will continue to provide various opportunities to qualified engineers so that they can gain hands on systems engineering developmental experience that will broaden and improve their discipline knowledge, skills and abilities to lead complex projects such as GOES-R.

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BIOGRAPHIES

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