AC 2011-1064: TOWARDS MORE EFFECTIVE TEACHING STRATEGIES OF ITERATION AND SYSTEMS MANAGEMENT IN SPACECRAFT DESIGN

Hadi Ali, Purdue University

Hadi Ali is a Ph.D. student in the School of Engineering Education at Purdue University. He holds a B.S. in Aeronautics and Astronautics from Purdue University and a B.Sc. in Mechanical Engineering from the University of Jordan. He earned his Masters degree in Aeronautics and Astronautics from Purdue University majoring in aerospace systems design. He is also pursuing a Masters degree in Electrical and Computer Engineering at Purdue. Hadi is a student member of AIAA, IEEE, ASME, and SAE.

Robin Adams, Purdue University, West Lafayette

Robin S. Adams is an Assistant Professor in the School of Engineering Education at Purdue University. She led the Institute for Scholarship on Engineering Education (ISEE) as part of the Center for the Advancement of Engineering Education (CAEE). Dr. Adams received her PhD in Education, Leadership and Policy Studies from the University of Washington, an MS in Materials Science and Engineering from the University of Washington, and a BS in Mechanical Engineering from California Polytechnic State University, San Luis Obispo. Dr. Adams' research is concentrated in four interconnecting areas: cross-disciplinary thinking, acting, and being; design cognition and learning; views on the nature of engineering knowledge; and theories of change in linking engineering education research and practice.

Towards More Effective Teaching Strategies of Iteration and Systems Management in Spacecraft Design

ABSTRACT

We propose effective teaching strategies to help teams of students in spacecraft design projects in the first or second semester in the sophomore year in the aerospace engineering curriculum move from being "beginning designers" to being "informed designers." The focus here is on one dimension in the Matrix of Informed Design that is suggested by Crismond and Adams (in review), namely, Haphazard or Linear versus Managed and Iterative Designing. The objective is to instill in students systems management skills and greater appreciation for iteration in design by providing a unique context. This will be provided through the use of the development story of the Apollo Lunar Module as a historical case study in which students can observe design iterations in the larger system in which the spacecraft existed, with particular emphasis on cost and schedule. In this paper we describe the teaching strategy and the elements of the historical case as a unique way to contextualize design learning by understanding the kinds of iteration that occur and why they occur; implementing and assessing the strategy will be a focus of future work.

1. Introduction and Motivation

Spacecraft design is highly iterative. Like many complex systems, problems faced during the design of a spacecraft often have more than one solution. The fact that an operable space system capable of meeting mission requirements within imposed constraints including (but not restricted to) mass, cost, and schedule makes spacecraft design a highly iterative process of exploring optimal solutions that have conflicting requirements. Therefore, systems thinking and iterative design practice are important aspects in the development of space vehicles and space systems that involve a variety of technologies and subsystems.

Opportunities to understand the iterative aspects of spacecraft design are limited. Methods to develop students' awareness of iteration beyond introducing iteration in different design models are lacking in engineering education in general, and in aerospace engineering education in particular. One of the challenges being faced by faculty in the field of aeronautics and astronautics is teaching space systems design and engineering in an effective way. Unlike traditional engineering fields, including the closely related field of aeronautics, teaching space systems design and engineering is difficult because of the lack of opportunities to go through an entire cycle from system conception to system operation in one or two design courses. Iterative design tasks that are introduced in sophomore design courses in the aerospace engineering curriculum cannot be iterative in the grand scale in which students must consider the real impact of technical design iterations on cost and schedule iterations. This is further complicated by the fact that students have limited, if any, exposure to systems thinking and systems design at the sophomore year level because of the lack of interaction with different disciplines outside aerospace engineering. Efforts have been made to restructure an entire engineering curriculum to foster systems building skills, like the Conceive-Design-Implement-Operate (CDIO) initiative[2]. Much of the research in space systems design conducted in academia emphasizes computational modeling with a focus on predicting system capability and behavior[3,4]. Recent initiatives like CubeSat[5], suggest cost-effective, standard satellite modules to deliver educational experience of building spacecraft to university students. Yet another example that fosters systems thinking is the utilization of design competitions similar to those administered by the American Institute of Aeronautics and Astronautics (AIAA).

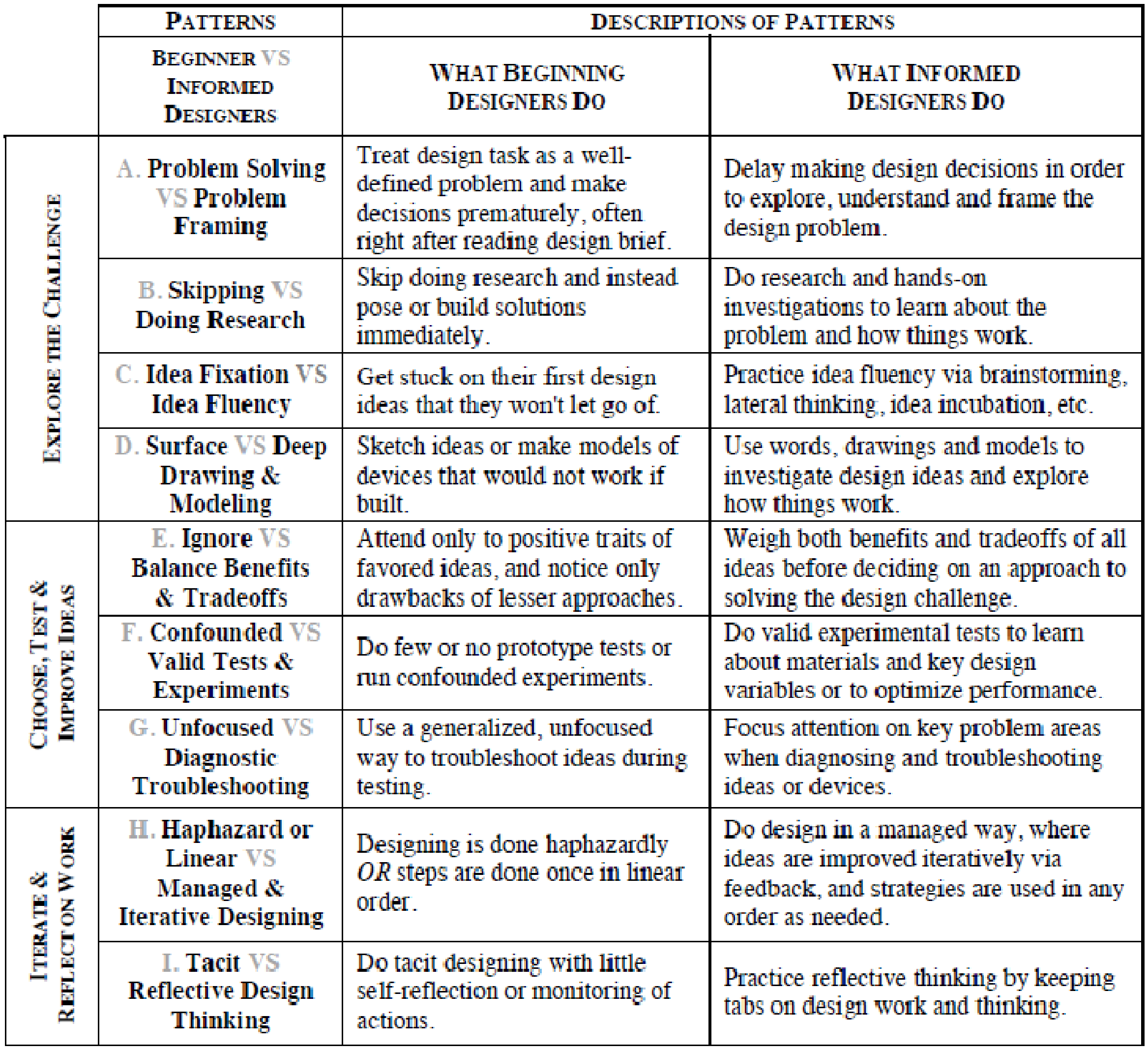
Learning about iteration is a key part of becoming an informed designer. The pedagogical objective of the teaching strategy presented in this paper is to move students from being "beginning designers" to being "informed designers." We suggest a teaching strategy that can be used in a team setting. This paper draws on the framework of Crismond and Adams (in review) to create a scaffolded design learning experience that helps student move from "Haphazard or Linear Designing" to "Managed and Iterative Designing." In particular, we present a case on the iterative aspects of spacecraft design as an effective teaching strategy for learning about iteration. This case is based on the Apollo Lunar Module (LM) as an interesting example of building a manned space vehicle that had no similar precedent. The case illustrates the highly iterative process of designing spacecraft by looking at possible relationships between the profile of vehicle configuration changes, and consequently, impacts on cost and schedule predictions.

2. Background

In Crismond and Adams (in review), a great effort has been made to integrate the vast literature on design, and create a Matrix of Informed Design tool that a design 'educator' can use to monitor progress in design learning during design experiences. The "starting point" and the "end point" of the journey of design learning are defined in such a way that neither underestimates nor overestimates the expectations about the students. The starting and end points of the Matrix "focus on the rank beginner and the advanced novice or "informed" designer, the latter who demonstrate capabilities articulated in research on design cognition and learning and described in engineering education and STEM education standards."[1]

The Matrix contains a "set of nine observable engineering design strategies and habits" (Fig. 1) that may be assessed and compared between a "beginning designer" and an "informed designer."[1] While the paper talks about "expert" designers requiring at least ten years to reach the level of mastery of their fields by consistent effort in organizing knowledge, "informed designers" are different from expert designers. Bransford, et. al., describe *expert designers* as showing salient patterns, and have much situation-specific knowledge and easily remembered cases[6]. In contrast, a focus on informed designers is a focus on a realistic target for undergraduate education. Crismond and Adams (in review) characterize *informed designers* as being able to "retrieve their knowledge less flexibly, and encounter more instances of disconnected knowledge and isolated facts, in part because they hold in mind few experiential cases and have yet to achieve what could be considered extensive practice."[1] *Beginning* *designers* show less effective design approaches when contrasted with the more effective strategies of informed designers. Informed designers have formal training or experience, but they cannot teach what they know to beginning designers.

For the purpose of this paper, we focus on one dimension, Pattern H, Haphazard or Linear versus Managed and Iterative Designing. As shown in Fig. 1, Pattern H emphasizes the iterative aspects of design and design learning. In particular, the Informed Design Matrix characterizes informed designers in Pattern H as being able to *do design as an iterative process, improving ideas and prototypes based on feedback, and use strategies in any order, as needed, in a managed and systematic way*[1].



	PATTERNS	DESCRIPTIONS OF PATTERNS	
	BEGINNER VS INFORMED DESIGNERS	WHAT BEGINNING DESIGNERS DO	WHAT INFORMED DESIGNERS DO
EXPLORE THE CHALLENGE	A. **Problem Solving** VS **Problem Framing**	Treat design task as a well-defined problem and make decisions prematurely, often right after reading design brief.	Delay making design decisions in order to explore, understand and frame the design problem.
	B. **Skipping** VS **Doing Research**	Skip doing research and instead pose or build solutions immediately.	Do research and hands-on investigations to learn about the problem and how things work.
	C. **Idea Fixation** VS **Idea Fluency**	Get stuck on their first design ideas that they won't let go of.	Practice idea fluency via brainstorming, lateral thinking, idea incubation, etc.
	D. **Surface** VS **Deep Drawing & Modeling**	Sketch ideas or make models of devices that would not work if built.	Use words, drawings and models to investigate design ideas and explore how things work.
CHOOSE, TEST & IMPROVE IDEAS	E. **Ignore** VS **Balance Benefits & Tradeoffs**	Attend only to positive traits of favored ideas, and notice only drawbacks of lesser approaches.	Weigh both benefits and tradeoffs of all ideas before deciding on an approach to solving the design challenge.
	F. **Confounded** VS **Valid Tests & Experiments**	Do few or no prototype tests or run confounded experiments.	Do valid experimental tests to learn about materials and key design variables or to optimize performance.
	G. **Unfocused** VS **Diagnostic Troubleshooting**	Use a generalized, unfocused way to troubleshoot ideas during testing.	Focus attention on key problem areas when diagnosing and troubleshooting ideas or devices.
ITERATE & REFLECT ON WORK	H. **Haphazard or Linear** VS **Managed & Iterative Designing**	Designing is done haphazardly *OR* steps are done once in linear order.	Do design in a managed way, where ideas are improved iteratively via feedback, and strategies are used in any order as needed.
	I. **Tacit** VS **Reflective Design Thinking**	Do tacit designing with little self-reflection or monitoring of actions.	Practice reflective thinking by keeping tabs on design work and thinking.

Fig. 1. The Matrix of Informed Design links nine Patterns of Design Behaviors (Column 1) to descriptions of how Beginning Designers (Column 2) versus Informed Designers (Column 3) do those strategies[1].

Different suggested teaching strategies for each pattern in the Matrix of Informed Design are also discussed as examples of ways to move design students from being beginning designers to being informed designers[1]. For Pattern H, these include:

1. <u>Design storyboards:</u> Students are asked to document how challenges have been overcome over time through sketches or digital snapshots accompanied by short verbal descriptions.
2. <u>Project and time management:</u> Students develop a timeline with special milestones where feedback and peer evaluations on prototypes or presentations are provided.
3. <u>Instruction and scaffolding for systematic design:</u> Students can be asked to simply read a book on design process as well as the instructor making them aware of the iterations that took place during their design process. Reviewing case studies of strategic design thinking "can help students realize the power and utility of iterative design."[1] Reflection in various contexts can be very helpful as well[32].
4. <u>Risk-taking and iteration:</u> Offering students with lessons about learning from failures, approaching and accepting them, can be very effective in allowing students to appreciate iteration and take more risks while designing.

"Instruction and scaffolding for systematic design" was selected as an appropriate teaching strategy to illustrate the role of iteration in spacecraft design with respect to cost and scheduling issues. In particular, we claim that the case of the Apollo Lunar Module has the capacity to provide rich opportunities to effectively teach students the role of iteration in design, the ways spacecraft design is iterative, and to develop an awareness of iteration as a characteristic of informed design. The rationale for this decision is based on the idea of contextualization as a proven concept in teaching and learning[50] because it provides situated examples for students to connect with their own frames of reference. Contextualization allows the introduction of environments beyond the students' reach and helps them make relationships with such environments in a more sensible and appealing way. In a recent paper to the American Society for Engineering Education on the CDIO initiative in aerospace engineering, contextualization is found to be a compelling learning approach that goes beyond the regular educational environments:

> "The evidence for adopting a contextual learning approach is compelling. This approach encourages students to choose specific careers and remain in their respective career preparation programs. Learning environments and experiences set in professional contexts open students' minds, enabling them to become more thoughtful, participative members of society and the workforce. Moreover, a contextual learning approach assists students in learning how to monitor their own learning so that they can become self-regulated learners."[52]

As a point of clarification, our proposed strategy is not project based, because of the belief that real impact of design iterations on cost and schedule iteration are very hard to capture in any educational setting, given the realization of the real complexity of space projects in the scale of the Apollo or the Space Shuttle programs.

3. Creating the Teaching Tool

In this section we describe the process of creating a teaching tool to introduce and emphasize the concepts of design iteration and systems management to students involved in spacecraft design projects. The teaching strategy draws on the case of the Apollo Lunar Module and the method of narrative research design[51] to provide students with a scaffolded and contextualized learning experience. The uniqueness of the Apollo LM makes the decision to study its development very attractive for the purpose of exploring themes in designing spacecraft that have no precedence. Reading a book, like Tom Kelly's book, *Moon Lander: How We Developed the Apollo Lunar Module*[33], provides an opportunity for students to act as narrative researchers[51]. The narrative in Kelly's book illustrates how iteration in design occurred while designing the LM and how it affected and was affected by the budget available from Congress at that time of the Apollo program, and the pressure of national schedule commitments (i.e., landing a man on the Moon and returning him safely back to Earth before the end of the decade). A unique value of this book is that it tells a story that cannot be inferred from technical reports because such reports usually do not give details of the *changes of configuration* of the vehicle that took place[34,35,36,37,38].

The goal of this teaching tool is to facilitate students' development as informed designers by helping them understand (1) how spacecraft design is highly iterative, (2) the kinds of technical iterations that have an impact on the larger design project through cost and schedule iterations, and (3) reasons why a systems perspective is necessary for spacecraft design.

The narrative research design procedure is summarized as follows:

1. *Identify the phenomenon to explore.*
2. *Purposefully select an individual from whom the phenomena can be learned more about.*
3. *Collect the story from that individual.*
4. *Organize the story elements into the problem solution narrative structure.*

In the following sections we provide details for each step.

Step 1. Identify the phenomenon to explore.

In this study the phenomenon is design iterations during the development of the Apollo LM.

Iteration plays a central role in design

Design iteration is an essential phenomenon in designing complex systems like spacecraft and space systems. Modeling the design process has been extensively studied, particularly in terms of modeling relationships among design activities[7,8]. Iteration is present in many design process models, and has also been studied[9,10]. For example, Safoutin discussed how manipulating iteration could improve design[11]. Iteration has been described as a "fundamental feature of design activity that signifies a goal-directed process of revisiting aspects of a design task in which the goal is a solution that is internally consistent with an understanding of the problem. Iterations mark awareness that neither the problem nor the goals are well-defined, and are the result of attempts to reconcile ambiguities and contradictions. In cognitive models of design, aspects of this process are described as problem and solution co-evolution."[12]

Browning defines an iterative design process as “one where multiple passes are required for the design to converge to suit an array of sometimes conflicting specifications.”[13] Another definition of iteration is provided by Eppinger as “the repetition of activities to improve an evolving design.”[14] The repetition or rework generates a new, modified design (output) as a result of some new information, activities, and/or failure to meet design objectives (more generally, new input)[9]. The new “input” can be in the form of[13]:

(1) Upstream (previously worked) activities changing their outputs
(2) Concurrent, coupled activities changing shared assumptions
(3) Downstream activities feeding back changes as errors and incompatibilities are discovered.

Iterations can be intentional (planned) to create useful information required in the design process, or they can be unintentional (unplanned) “resulting from new information arriving at the wrong time in the process.”[13]

Spacecraft design is highly iterative

Improving the spacecraft design process requires *understanding* that process. This leads to the question of what do we know about the spacecraft design process? The design process, in general, can be viewed “as a set of complex activities with discernable interrelationships.”[13] In the case of the spacecraft, the designer has to deal with different scientific requirements and engineering disciplines that must be considered concurrently and as a part of the integrated design process and optimization. The complexity of activities and interrelationships amongst them required the emergence of the field of space systems engineering. This is necessary to integrate the design process and its accompanying tradeoffs between subsystems such as propulsion, power sources, guidance and control, and communications.

One of the definitions of space systems engineering is given as[15]:

> “The art and science of developing an operable system capable of meeting mission requirements within imposed constraints including (but not restricted to) mass, cost, and schedule.”

As subsystems become more sophisticated, as it is the case in spacecraft design that has multiple sets of conflicting requirements, requirements and capabilities become difficult to align. As a result, tradeoffs and compromises along the path of project completion will be required[15,16]. Familiarity and literacy in a broad set of disciplines become necessary in such design processes as multiple iterations of design decisions will be required to achieve an optimal solution.

Spacecraft design involves particularly broad challenges because iterations occur in two major levels. First, iterations occur in the mission analysis level when the top-level parameters are being examined. This includes parameters of launch options, transfer trajectories and overall mass budget (propellant, platform, and payload), without regard to details of the subsystems[16]. The details of the payload itself and the accompanying subsystems represent another, second, level of iterations which is often being simply assumed at the early stages or drawn upon similarities with previous missions. The decisions being made during tradeoffs and complexities at this level require a wide range of analysis in disciplines such as communications, power, thermal control, propulsion and so on. Mass growth is a typical feature in spacecraft development projects (mass growth refers to the situation that happens to the spacecraft as its mass increases during the development process due to additions or reconfigurations). It is the task of the systems engineer to resolve technical tradeoffs as the project progresses.

What makes spacecraft design complex and highly iterative is the interaction between these two levels of iterations in addition to the fact that iterations are not purely technical; there are social factors that take place in all these iterations. The products of the aerospace industry represent a pinnacle of research and development enterprise[17] but they are paradoxical: in one sense they are innovative, but in the other sense, with thousands of engineers working on the solution of several problems, bureaucracy plays an important role. How can innovation and bureaucracy coexist? This is related to the social aspect of designing space vehicles, where the ultimate success does not only depend on technical solutions, but also on managerial and social solutions. Max Weber was one of the pioneers to indicate in his theory of social and economic organization that in modern organizations the structure promotes and sustains bureaucracy[18].

In the early developments of spacecraft in the U.S., systems management was a result of conflicting interests and objectives between the major groups involved in the development process. The four major groups of people who were involved were the scientists, the engineers, the managers, and the military officers representing the customer. These groups were, unconsciously, the promoters of systems management. Systems management can be defined as: “A set of organizational structures and processes to rapidly produce a novel but dependable technological artifact within a predictable budget.”[17] One can see that all the groups are present in this definition; the customer seeking rapidability, scientists seeking novelty, engineers seeking dependability, and managers seeking predictability of budget (cost and schedule) [17]. Systems management seems to be surviving in today’s aerospace industry because of two major reasons; first because it emerged unconsciously by the various groups, and second because everyone is present in its processes[17].

Design iterations impact cost and schedule iterations

Iteration has been found to impact the time required to complete a development cycle[21,28]. Thus, to accelerate the design development process (1) faster iterations, and (2) fewer iterations are required[9]. Faster iterations can be achieved by improved coordination, while fewer iterations may mean a design with less quality[13]. In complex systems developments, it is the nature of such project that they are coupled and iterative[11,20,21]. Thus, the design of complex systems is not achievable without multiple passes. Many recent design models have identified the need for iteration in design, and therefore iteration in design is well documented in literature[22,23,24,25,26]. von Hoppel discussed the importance of partitioning tasks in large projects and talked about different strategies to achieve that[19]. Recently, the NASA Systems Engineering Handbook documents iteration as part of the design process[27].

AitSahlia, et. al., discussed the extent to which planning concurrent activities in engineering projects is valuable[29]. Susman’s book is one of many that discuss the role that different management tools play in improving the integration of design and manufacturing[20]. Blanchard and Fabrycky is another example of the discussion on management tools as particularly applied in the context of systems engineering[22]. Several types of design tools have been developed to assess design[24,25,26,27,30].

Yet, the relationship between iteration in spacecraft design and its impact on a project cost and schedule is not fully understood in the spacecraft development process. Understanding the relationship between technical design iterations and cost and schedule iterations may enhance the ability of project managers to accurately predict budgets, which is crucial for high risk, high cost projects like space projects.

Why is iteration not thoroughly addressed early in the design process as a factor affecting cost and schedule? Browning tried to answer this question in his work on aircraft design. While there are similarities between the aircraft and spacecraft projects, mainly because both are high-risk, high-cost projects, spacecraft are unique because they are not produced in volume, which makes their developmental cycles inherently different. Here is a list that summarizes answers to the question of why iteration in the aircraft industry is not thoroughly addressed[13]:

Table 1. Summary of answers to why iteration in the aircraft industry is not thoroughly addressed[13].

Why iteration in the aircraft industry is not thoroughly addressed?

Reason	**Interpretation**
Unperceived iteration	In the design process, awareness of iteration is not achieved by everybody in a company.
Atypical circumstances	Most iterations are unintentional, so most participants in the project including the mangers consider such iterations as unique cases, and therefore they are not thoroughly addressed.
Process iteration is schedule driven	This means that only a prior judgment is used to accommodate iteration with no further understanding of the phenomenon.
Iterations are made unlikely to happen through “conservative” but not “robust” design.	
Iteration is considered a more detailed issue to consider in the early planning phases.	

Iteration is well appreciated and acknowledged in the early design cycles, but iteration is actually more frequent and has more serious impacts in the later stages of the design process, especially when testing occurs.

Iterative aspects of spacecraft design are not often emphasized or used to help students learn

Teaching spacecraft design as a linear process, moving from one step to the other in one direction, can limit students' understanding of important iterations in design and encourage design misconceptions. This is complicated by the fact that students do not typically have a chance to build and test spacecraft designs. Testing is known to be an important step in moving from one stage to the other in the progress of the project. In fact, iteration has been defined as "cycles of proposal, testing, and modification of an evolving design."[31]

Step 2. Purposefully select an individual from whom the phenomena can be learned more about.

The individual selected is Thomas Kelly, the father of the Lunar Module. The case of the Apollo LM provides opportunities to effectively teach students the role of iteration in design, the ways spacecraft design is iterative, and to develop an awareness of iteration as a characteristic of informed designer. Fig. 2 below illustrates the development of the LM configuration from beginning to end.

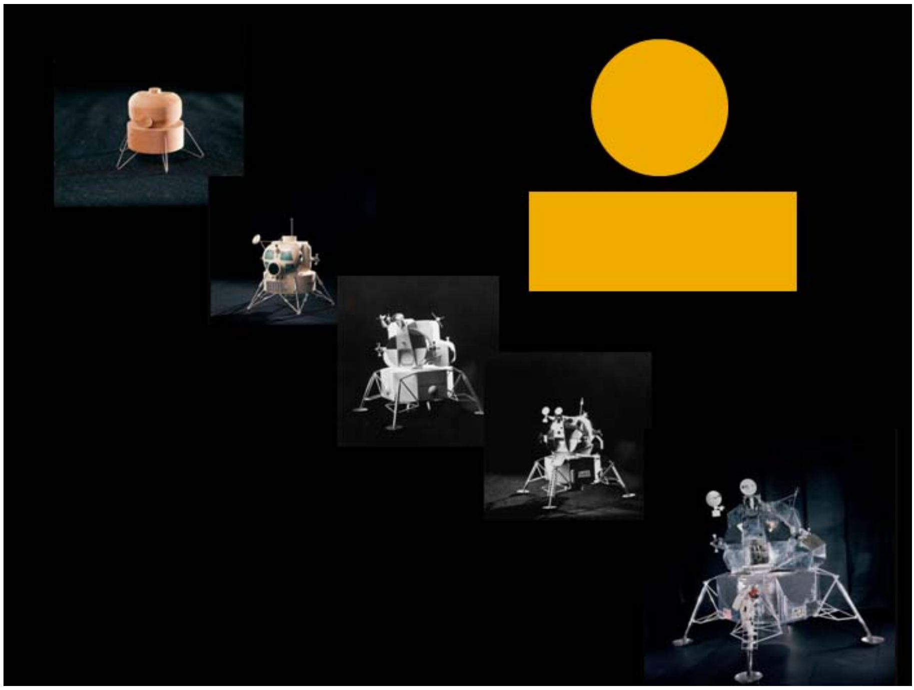


Fig. 2. Composed image showing the overall configuration development of the Apollo LM[49]. The image on the top right corner shows the schematic that the LM engineers used to use to describe their concept simplistically: a descent stage and an ascent stage.

Step 3. Collect the story from that individual.

We propose the book *Moon Lander: How We Developed the Apollo Lunar Module* by Tom Kelly, the father of the LM[33], as a useful resource for cataloguing and understanding design iterations for the Apollo LM. In this book, Kelly records and presents a personal, professional experience during the period of his involvement in the development of the LM with Grumman. The story has the following unique characteristics:

- It is an individual experience
- It provide the chronology of experiences as experienced by the individual
- It has some side descriptions of experiences by other individuals
- It has the form of restoring of the LM development in specific, and the Apollo program in general
- It includes detailed descriptions of contexts and settings
- There was no collaboration with others in writing
- The Apollo engineers where not necessarily designing experts in developing spacecraft as this was something new to everyone. Their attributes match somehow the attributes of informed designers as discussed before.

All these characteristics make Kelly's story suitable for developing a case study since it provides sufficient detail to illustrate design iterations. Kelly has also published papers on the features of the LM[34,35,36,37,38] for the American Institute of Aeronautics and Astronautics (AIAA) that are more technical in nature. Kelly also wrote a masters thesis on a closely related topic after his involvement with the Apollo program entitled *The Dynamics of R&D Project Management*[39]. Personal stories from people involved in space explorations at different positions also exist. A summary of some of the existing literature in this area is provided in Table 2.

Table 2. Summary of similar narration stories from individuals who were involved in the space program.

Reference and Title	**Occupation of Main Character**	**Narrated by**
Hansen (2006) First Man: The Life of Neil A. Armstrong[40]	Astronaut	Narrator
Collins (2009) Carrying the Fire: An Astronaut's Journeys[41]	Astronaut	Himself
Cernan and Davis (2000) The Last Man on the Moon: Astronaut Eugene Cernan and America's Race in Space[42]	Astronaut	Himself with a narrator
Kluger and Lovell (2006) Apollo 13[43]	Astronaut	Himself with a narrator
Kranz (2009) Failure Is Not an Option: Mission Control From Mercury to Apollo 13 and Beyond[44]	Mission Control	Himself
Kraft (2002) Flight My Life in Mission Control[45]	Mission Control	Himself
Slayton (1995) Deke!: An Autobiography[46]	Mission Control	Himself
Shirley (1999) Managing Martians[47]	Manager	Herself
Bizony (2006) The Man Who Ran the Moon: James E. Webb, NASA, and the Secret History of Project Apollo[48]	Manager	Narrator

Step 4. Organize the story elements into the problem solution narrative structure.

For this step, the framework by Adams for coding iterative activity is used[12]. The framework is based "on a cognitive model describing underlying mechanisms of iteration as well as schemes for classifying iterative cycles and processes."[12] To operationalize iteration in this framework, iteration is understood as a goal-directed cognitive process. To identify and document iterations in Kelly's story, two features for each iteration in the story were coded as follows, see Fig. 3.:

- First feature: That which triggered the iteration (by an information processing or activity)
- Second feature: A change to a design state (process, problem, or solution element).

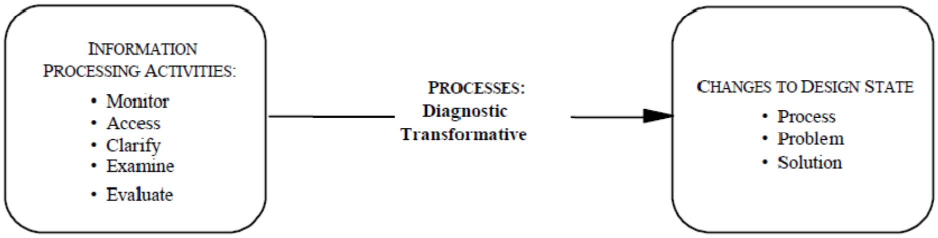


Fig. 3. The cognitive model of iteration in design that will be used in coding Kelly's story[12] .

We have selected Chapter 9, *Problems, Problems!* from Kelly's book to illustrate the coding process in Step 4. This chapter is very useful because it outlines a set of iterations that had implications across cost and scheduling, including the sequencing of manned missions that eventually led to the manned LM landing before the end of the decade. Several of the interactions between iterations in the LM design and the larger system of the entire Apollo program are also discussed in this chapter.

Step 4 is illustrated below, Table 3, for problems regarding one subsystem of the LM as narrated by Kelly, namely, Propulsion and Reaction Control System Leaks.

An example of the coding in Step 4 is described for the first row in Table 3: "Leaks occurred on both the pressurant (helium gas) and the propellant fuel and oxidizer sides of the system,"[33] (first column). This prompted a series of activities to address this technical issue: "we proposed using welded or brazed joints to eliminate mechanical connections in fluid systems," [33] (second column). As such, this sequence of activities was coded as a Solution kind of iteration, as the change in the design state resulted in change to a solution.

Another example is the second row in Table 3: "None of our mechanical joint designs were leak-tight and even the brazed joints leaked," [33] which resulted in the change in the design state: "We stopped the leaks on the heavyweight rigs at Bethpage by replacing gaskets and O-rings and tightening bolts and threaded fasteners to their allowable torque limits." [33] We coded this as a Solution kind of iteration. One may notice that the kind of change (process, problem, or solution), can be more than one kind at the same time, as there is a co-evolution of problems and solutions being observed.

Table 3. Coding of iteration as narrated in Chapter 9 in Kelly's book[33] for Propulsion and Reaction Control System Leaks.

What triggered an iteration?	Changes to a Design State	Kind of Change (Process, Problem, Solution)
“Leaks occurred on both the pressurant (helium gas) and the propellant fuel and oxidizer sides of the system. Although no leaks were tolerable anywhere in the systems, propellant leaks were extremely serious because the propellants were highly toxic volatile liquids, and being hypergolic, their fumes would ignite if combined.” (p. 127)	“Without working out the details at that time, we proposed using welded or brazed joints to eliminate mechanical connections in fluid systems and mechanical energy absorbers in the landing gear to eliminate the potential leakage of hydraulic shock absorbers. We chose stainless steel tubing joined by high temperature nickel-silver brazing for the propulsion and RCS systems to minimize the number of mechanical joints.” (p. 127)	Solution
“None of our mechanical joint designs were leak-tight and even the brazed joints leaked, unless they were perfect, with full, even flow of the brazing material over the contact area of the joint.” (p. 127)	“For a while we blamed the sniffers (too sensitive!), but we found that many of the suspect joints would also show leaks in the common, low-tech bubble test with detergent solution. We stopped the leaks on the heavyweight rigs at Bethpage by replacing gaskets and O-rings and tightening bolts and threaded fasteners to their allowable torque limits.” (p. `128)	Solution
“[Lynn] made a special trip to Bethpage to demand that Propulsion and RCS be made leak-tight, no matter what it took.” (p. 128)	“Two additional sets of rigs, heavyweight HA-3 and HD-3 and lightweight PA-1 and PD-1, had been delivered from Bethpage to White Sands, and although they had improved mechanical joint designs, they still leaked.” (p. 128)	Problem/Solution,
“Radcliffe started with Joe Gavin and Bob Mullaney and worked his way down through the LM management hierarchy, preaching against the evil of leaks and the need to reform our designs without delay. When he reached me I was shocked by what I heard. I had not realized that the rigs were still leaking badly despite the improved seal designs we had provided.” (p. 129)	“Carbee and his fluid systems design group leaders joined the meeting at my request, and after Radcliffe repeated his message of warning we discussed what to do next. Radcliffe's opinion was unequivocal: "Eliminate all mechanical joints, and learn how to make brazed joints that don't leak." We agreed to work toward this goal.” (p. 129)	Process

“In the ensuing week we eliminated the AN (army-navy standard), Gamah, and other fittings … we brazed these components directly into the system with high-temperature nickel silver brazing alloy … For replacement, the Manufacturing Engineering group worked out a technique of cutting out the component ...” (p. 129)	“This made maintenance of these fluid systems more difficult and time-consuming, but if we made the brazes properly, they did not leak. It was necessary to X-ray every brazed joint ... Portable X-ray equipment was used to inspect the joints in place on the shop floor, but no one could work in the immediate area while X-ray was in progress. There were still some areas where we retained mechanical connections ... Large opening in the tanks were necessary for cleaning, inspection, and installation of quantity gauging sensors ... Even Radcliffe found the improved system design acceptable, except that he occasionally had to reheat brazed joints or tighten bolted flanges that had developed leaks.” (p. 129-130)	Process/Solution
“Leaks continued as an occasional nuisance item in cold flow and at White Sands until the LM-1 fiasco in June 1967. LM-1 was delivered in the midst of shakedown problems with the spacecraft assembly and test operation in Pant 5, Bethpage. When we delivered LM-1, Grumman and the local NASA inspectors thought we had a leak-tight spacecraft ... Soon after it was received at KSC, LM-1 was found to have wide-spread leakage in the propulsion and RCS systems. The people at Cape Kennedy quickly characterized Grumman's first-worthy spacecraft that we had proudly, if tardily, shipped as a "piece of junk that leaked like a sieve." ... We initially thought the cape's findings were due to differences in leak detection procedures and equipment.” (p. 130)	“To test this hypothesis a QC crew from Cape Kennedy came to Bethpage and performed leak tests on systems in LM-2 and LM-3 that had been found leak-tight at Bethpage.” (p. 130-131)	Process/Problem
“Discouragingly, they found some leaks that had escaped detection by the home team. Moreover, the leaks were real-on both LM-1 at the cape and LM-2 and LM-3 some of the leaks detected by the sniffers could also be seen in the bubble test.” (p. 131)	“Although I was unsure why this happened, I declared that we would adopt the cape leak test regimen and have experienced cape inspectors train our people in its use …” (p. 131)	Process/Problem
“Embarrassed and responding to pressure from NASA, Joe Gavin became directly involved in the leak problem.” (p. 131)	“At my recommendation he put Will Bischoff, deputy Structural Design Section head, in charge of an intensive leak fix effort.” (p. 131)	Process/Problem

“The bolted flanges on the tanks were the worst problem, followed by the few other smaller mechanical component connections that had survived my earlier purge.” (p. 131)	“Bishop consulted with the tank manufacturer … and with the O-ring and sealing experts around the country, and developed a new design for the tank flanges. It had dual O-rings, revised groove dimensions and tolerances, and a test port between the two O-rings to detect leakages. Test samples performed very well ... we replaced the tank flanges in LM-1 with an interim improved design ... Bishop's team also developed an improved dual O-ring flange design for pipe-mounted components ... the bishop team went over our brazing process thoroughly ... With time, the percentage of first-time acceptable and leak-tight brazes increased and the number of reheats went down.” (p. 131)	Solution
“LM-1 was finally made leak-tight at the cape after three months of intensive effort, aided by six of Radcliffe's best "leak fixers" on loan from White Sands. The damage to Grumman's reputation was severe. The next spacecraft we delivered, LM-3, was pounced upon savagely when it arrived in June 1968 and immediately checked for leaks.” (p. 131)	“This time we had invited the Cape Kennedy receiving inspection team up to Bethpage to join our people in the predelivery inspection and tests, so the cape people agreed that LM-3 was leak-tight when shipped.” (p. 131-132)	Process
“Propulsion and RCS leakage remained a concern throughout the duration of the LM program.” (p. 132)	“Constant vigilance and retraining were required to attain leak-tight systems-any minor slip would soon be shown by a squealing sniffer in S/CAT or at Cape Kennedy. The frequency of leaks was greatly reduced from the mortifying debacle of LM-1 or the constant problems that had bedeviled Radcliffe at White Sands, but the occasional leakage that did occur reminded us constantly of the difficult and unforgiving nature of pressurized fluid systems in space. If it leaked in space or on the Moon there would be no way to stop it or replenish the precious lost propellant.” (p. 132)	Process

The following three examples from the coding above illustrate how the technical design iterations had impact on cost and schedule iterations during the Apollo LM design process:

- “Two additional sets of rigs, heavyweight HA-3 and HD-3 and lightweight PA-1 and PD-1, had been delivered from Bethpage to White Sands.”[33]

- "This made maintenance of these fluid systems more difficult and time-consuming." [33]

- "With time, the percentage of first-time acceptable and leak-tight brazes increased and the number of reheats went down." [33]

The first sentence shows implicitly how adding new test rigs required additional costs, and the second and third sentences are examples of how modifications had a scheduling impact. While they are not as rich as they may seem, Chapter 9 provides other examples from other subsystems of the LM, the accumulation of iterations in which caused delays in the manned space program.

Step 5. Reflect on the findings to identify and understand patterns of iteration.

This step should be conducted in a team setting in which team members discuss among themselves the key issues. They might focus on how the different teams of people interacted, and how that in itself is an interesting take away from the complex systems perspective. Crawley, et. al, describe one of the reasons why setting aerospace engineering education in the context of aerospace product development is important as "it aids in teaching the skills that [students] will need in the workplace." [52] Providing a narrative in the form of a case study gives the teams some guidance on how to "communicate and work in teams, and especially to act ethically and creatively." [52] While this statement was focused on engineering activities, the case study provides scenarios of "what would you do if you were in that situation?," and gives opportunities to explore more realistic, complicated, real-life situations.

Extending the application of the procedure

The teaching strategy presented above has illustrated three major activities: (1) *Reading* the narrative, (2) *Analyzing* the reading, and (3) *Discussing* the analysis within a design team. The teaching strategy can be extended by adding the step of (4) *Anticipating* similar problems that may occur in other subsystems. As a matter of fact, Chapter 9 of Kelly's book provides a discussion on problems encountered and solutions achieved to overcome problems with other subsystems such as ascent engine instability, stress corrosion, battery problems, and tank failures. It is expected that students would be faced with one or more of the following themes in the process[51]: ordinary themes (e.g., the number of battery rechargers allowed during ground tests compared to the actual flight of fully charged battery that would be used until depleted), unexpected themes, hard-to-classify schemes, and major and minor themes.

4. Conclusion and Future Work

Design iteration is an essential phenomenon in designing complex systems like spacecraft and space systems. In this paper we proposed a teaching strategy based on the case study of the Apollo Lunar Module to help students appreciate the role of iteration in spacecraft design projects and develop systems management skills. This is intended to move students in spacecraft design projects from being beginning designers to informed designers. We did not do the intervention; therefore, impact on learning is considered to be as a next step in future work.

Instead, the historical case is proposed as a unique way to contextualize design learning by understanding the kinds of iteration that occur and why they occur.

This proposal is unique in its approach to teaching about iteration in the spacecraft design process in two main ways: (1) it focuses on revealing aspects of iteration in the spacecraft design by exploring case studies from previous spacecraft projects; and (2) it uses a qualitative approach of narrative research to make evident themes of iteration and important variables. Both of these aspects are useful for students in spacecraft design courses and informed designers who are assigned the task of building real space systems with no prior history of similar developments.

A future goal is to develop more examples of applying the teaching strategy procedure, especially in an effort to provide a framework that relates technical design iterations to cost and schedule iterations, and to test the impact of this strategy on sophomore student's design learning. The teaching tool may also be used to help students predict other technical design iteration scenarios and the associated impacts on the larger system of the design project. Predictions may focus on the early stages of the design process or at times when critical decisions are made during detailed design and the consequences of these decisions. *Predicting* is an effort to anticipate "breakpoints" while *controlling* is an effort to avoid these "breakpoints." As such, the proposed teaching strategy may help students to develop skills in predicting breakpoints in design. This is similar to the role of configuration management and configuration control as practiced in spacecraft systems management. Configuration management is a process that makes people involved in changing a design of a spacecraft aware of what this change is going to affect and what its consequences are. The Jet Propulsion Laboratory over time learned by experience the typical profile of engineering changes and, consequently, how better to predict cost and schedule[17].

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