INTEGRATED

A Student's Guide to Systems Engineering

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Systems Engineering is not becoming integral to today's world – it is *integral. If you enjoy all your engineering courses, from thermodynamics to circuits to statics, you may have a passion for Systems Engineering and should check it out.*

– Dr. L. Dale Thomas, UAH ISEEM professor and Systems Engineering Eminent Scholar, former NASA engineer[1]

Huntsville is a Systems Engineering city, maybe the most important Systems Engineering city in the U.S. There is nowhere that is more suited to a Systems Engineering career than here.

– Dr. Paul Collopy, UAH ISEEM professor, former ISEEM department chair[2]

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The Glossary briefly defines all words and acronyms indicated in **bold** in the first primary usage.

The References page includes all the sources used to gather information for the project, as detailed in the following Endnotes.

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Introduction

My purpose in writing this student guide is to describe Systems Engineering for fellow undergraduate Industrial & Systems Engineering (ISE) students at The University of Alabama in Huntsville (UAH). This guide defines Systems Engineering and describes the system development process. The guide also demonstrates how Systems Engineering is an intriguing career field, using the development of the Apollo Lunar Module (LM) as an example of good Systems Engineering processes and practices, particularly in mission definition.

This guide was created through two class projects: a technical writing project on Systems Engineering in EH 301 "Technical Writing," taught by Mrs. Diane Singer in Fall 2017, and a Systems Engineering case study on the Apollo Lunar Module for ISE 627 "Engineering Systems," taught by Dr. L. Dale Thomas in Fall 2018.

Through this guide, I hope to help fellow students at UAH become excited about and interested in Systems Engineering and to help them discover their own passion.

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Figure 1. UAH Campus at Twilight[3]

Part 1 – Systems Engineering Defined

Systems Engineering is a field in which complex technical artifacts are integrated into a logical whole to fulfill a purpose and solve a problem.

Definition

First of all, consider definitions of the terms that make up this field:

Engineering

Engineering is essentially innovation with a purpose.[4] It takes a problem or a need that people experience in the world and designs a way to fix the problem by creating or modifying one or more components. Specifically, engineering uses mathematical and scientific knowledge and wisely applies it to a specific situation.[5] On the other hand, engineering may simply take existing technology and build upon it to make it better (increasing quality, efficiency, and so on), based on the need of the user.[6]

System

A **system** includes the following general components and considerations:

Purpose/Problem

As with engineering, any system includes a well-defined **purpose** or function to fulfill.[7] This purpose is the reason for creating the system – a human need (**problem**) that the engineered system will address and solve by producing products, services, or both.[8] The success of the system must be measured by how well it fulfills this purpose and fixes this problem.

Technical Components

All systems are composed of technical artifacts or **components**, each designed for a specific purpose and combined to form the full system.

Attribute

An **attribute** is an inherent, measurable characteristic of a system or component, as defined by its smaller components and functions.[9] When these attributes change, the system changes.[10]

Integration

All the parts of a system must be integrated to ensure that they work together (whether they have been originally designed that way or not), in order to fulfill the purpose for the system. Depending on the purpose and the interfaces between parts, this **integration** may cause the system to become quite complex.[11]

Interfaces

The various components of a system work together and connect with each other at the **interfaces**. Because of these interactions, system deficiencies are most likely to occur at the interfaces.[12] However, these interactions cause the system to fulfill its purpose, achieving a function greater than that which any of the parts could do on their own.[13]

Behavior

The system is designed for various activities to fulfill the purpose through the **behavior** of the components and system. These activities include all the occurring interactions between components.[14] Note that some systems include **emergent behavior,** which results from complex interactions of the system components and not from the combination of individual components' behavior. In that case, the system obviously is greater than the sum of the parts.[15]

Environment

Many outside factors influence the system, and the system often changes within or is changed by the **environment**.[16] These outside influences include the natural world, society, economics, regulations, politics, business, psychology, and other factors or unintended consequences. Thus, the success and behavior of a system are determined by many external factors, in addition to the technical components themselves.[17] On the human side, the **stakeholders** of a project include **operators** who interact with the system, **customer(s)** who commission the creation of the system, and anyone else who is directly or indirectly related to the system.[18]

Life Cycle

The **system life cycle** describes the system creation from an idea through design, development, integration, testing, delivery, and use to disposal.[19] The system life cycle is discussed in Part 2 of this guide.

The diagram below (Figure 2) shows a simplified model of a system composed of the elements listed above.

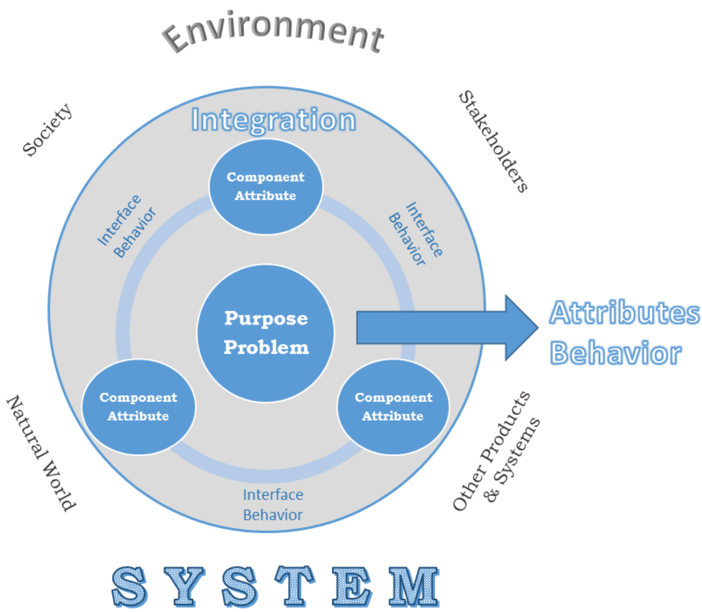

Figure 2. A System[20]

Systems Engineering

Thus, **Systems Engineering (SE)** takes multiple components and integrates them to form a system within a specific environment for a specific purpose – to fulfill a specific need in a dynamic world. Because SE takes into account so many different inter-relating parts, including the environment and varying constraints, it requires an iterative, logical, balanced, and multi-disciplinary approach – seeing the "big picture" of engineering.[21] The whole point is to choose the best design (there will not be a perfect design) while considering factors such as customer needs and preferences, economic impact, and level of risk – balancing objective measurements and data with subjective preferences.[22]

History

Consider a *very* basic history of Systems Engineering:[23]

The Development of Engineering

The original engineers were those who improved life for themselves and others by creating or modifying objects.

However, as society gained education and leisure time, creative minds thought of exotic ideas and inventions, some of which succeeded and some failed. The Scientific Revolution included these kinds of experiments, in which engineering shifted from the common person to the philosophic and scientific.

Then came the Industrial Revolution, which again changed the focus of engineering, in this case to the production of mass goods for the consumer.

The Birth and Growth of Systems Engineering

Interestingly, the following World Wars required engineering to flourish. Warfare technology focused on making technical artifacts; and, as these artifacts became more and more complex, systems began to enter the stage. Systems Engineering as a discipline developed during and after World War II as a way to organize the development of complex weapons systems.[24]

As the world, including the global commercial economy, began to grow again after the wars, everything became connected – especially through software and the Internet. Thus, new challenges that included many interfaces required increasingly complex solutions. In addition, engineering turned back to science and achievement for military weapons and status symbols. The Cold War and new military challenges of the twenty-first century kept Systems Engineering involved in warfare technology. [25]

Thus, Systems Engineering developed to make sure all parts of these complex projects (both military and consumer) were integrated to make the whole greater than the sum of the parts, to keep up with ever-greater technology.[26]

The Use of Systems Engineering Today

Today, the products of SE must relate to the ever-changing present world. The heart of the system is still the technological component that can be visualized and measured, but now many more factors from the environment are included – or are simply acknowledged as influences and analyzed as such.

In addition, SE is sometimes viewed as a burdensome set of busywork and management procedures to follow – not as a mindset and critical thought process of planning and organizing a system for a purpose. SE seeks to destroy the idea that engineering is a continual cycle of "try and fix" by focusing on the purpose of the system and understanding how it should and will work and how to create it *before* actually building it. [27]

Figure 3 below shows the general progression of engineering through history.

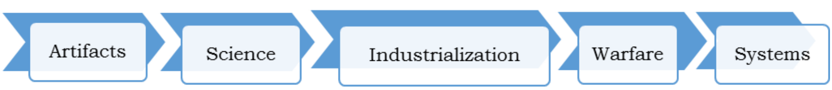

Figure 3. Summary of the Development of Engineering[28]

Example – Apollo Lunar Module

One example of a system developed during the rise of Systems Engineering is the Apollo **Lunar Module (LM)**. The LM was the part of the **National Aeronautics and Space Administration (NASA)** spacecraft that accomplished President John F. Kennedy's Apollo mission: to take men to the moon. Developed by the **Grumman Corporation**, the LM was composed of two combined stages: a descent stage that caused the whole LM to descend from the combined **Command and Service Modules (CSM)** in lunar orbit to the surface of the moon, and the ascent stage that left the descent stage behind on the moon, launched back up to dock with the CSM, and delivered the astronauts back to the spacecraft that would return them to Earth.[29] Every detail of the design and mission of the LM depended upon a myriad of factors – at the highest level, on the historical context of the Apollo mission. Figure 4 below details some of the major events pertaining to the LM up to the Apollo 11 landing.

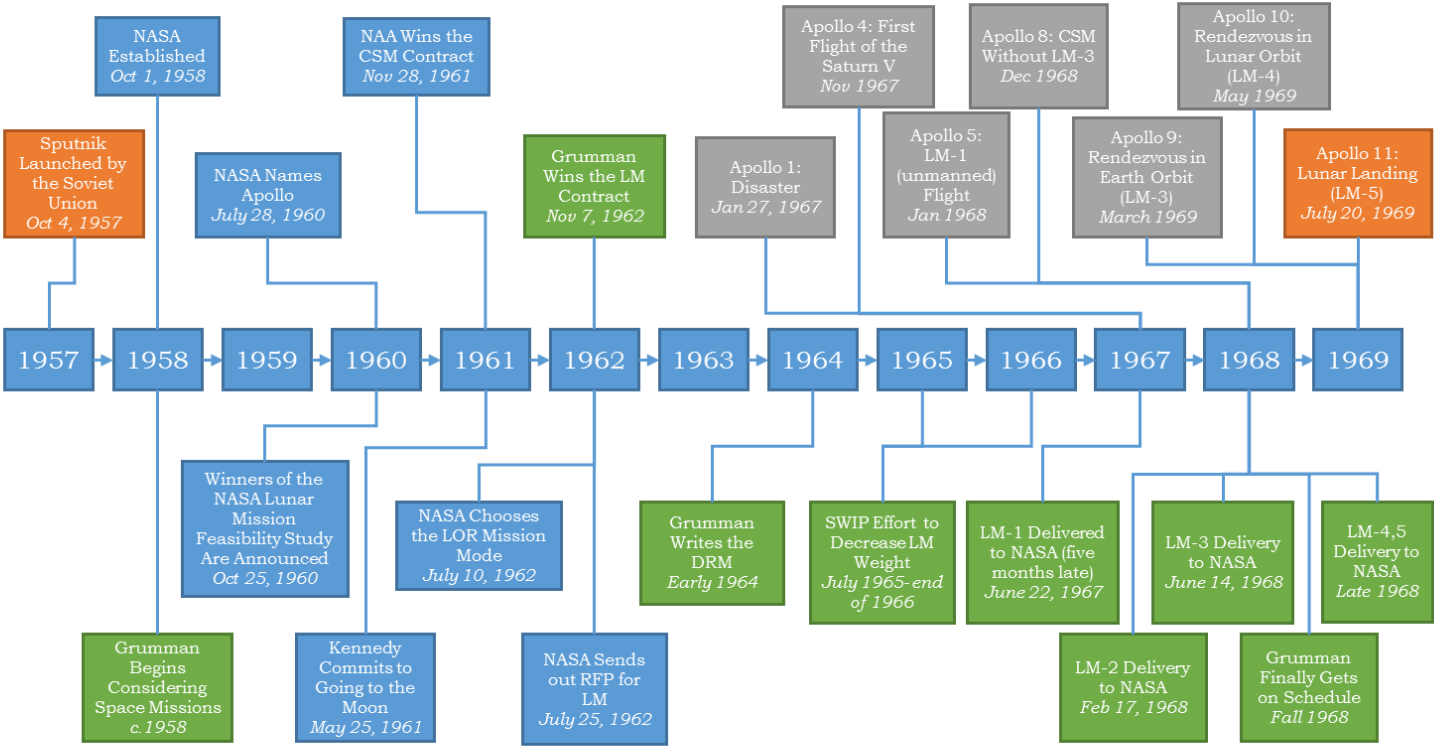

Figure 4. Major Events in Apollo History Regarding the LM[30]

Systems Engineering in the Apollo Program

Because the Apollo program was large and complex and was a military weapon (of a sort), it too made use of the new perspectives and methodologies of the budding Systems Engineering discipline. SE integrated all information across the system life cycle, from programmatic details (particularly schedule, which was perhaps the primary driver in the Apollo program, and cost) to mission planning to design to analysis to fabrication to assembly to testing to flight.[31] As noted before, the purpose of SE is to ensure that the system in question fulfills the mission set by the customer – in the case of Apollo and the LM, to “beat” the Soviet Union by putting a man on the moon and returning him home safely *first.*

Systems Engineering for the Lunar Module

The Grumman team realized the importance of using SE principles to bind together all of their work on the LM. For the team, SE hinged on carefully defining the **requirements** for the mission and the system functions and structure. These requirements were broken down farther (**requirements decomposition**) from the mission to the full system to the subsystems to the components, as applicable. Grumman also fully documented the interfaces and interactions of the system elements. The engineers compared the system performance to the requirements through **verification** and rigorously documented the whole process for the full life cycle.[32] This use of SE is very similar to that of industry today.

The Grumman LM development process illustrates several examples of primarily exemplary SE. Two glaring examples of SE problems on the LM are the mass and schedule management, which haunted the LM but through careful systems management were finally conquered.[33] However, the examples from the LM used in this guide focus on a more high-level aspect of the LM development up to Apollo 11: defining the mission.

Figure 5 below shows a cutaway of the LM and many of its components.

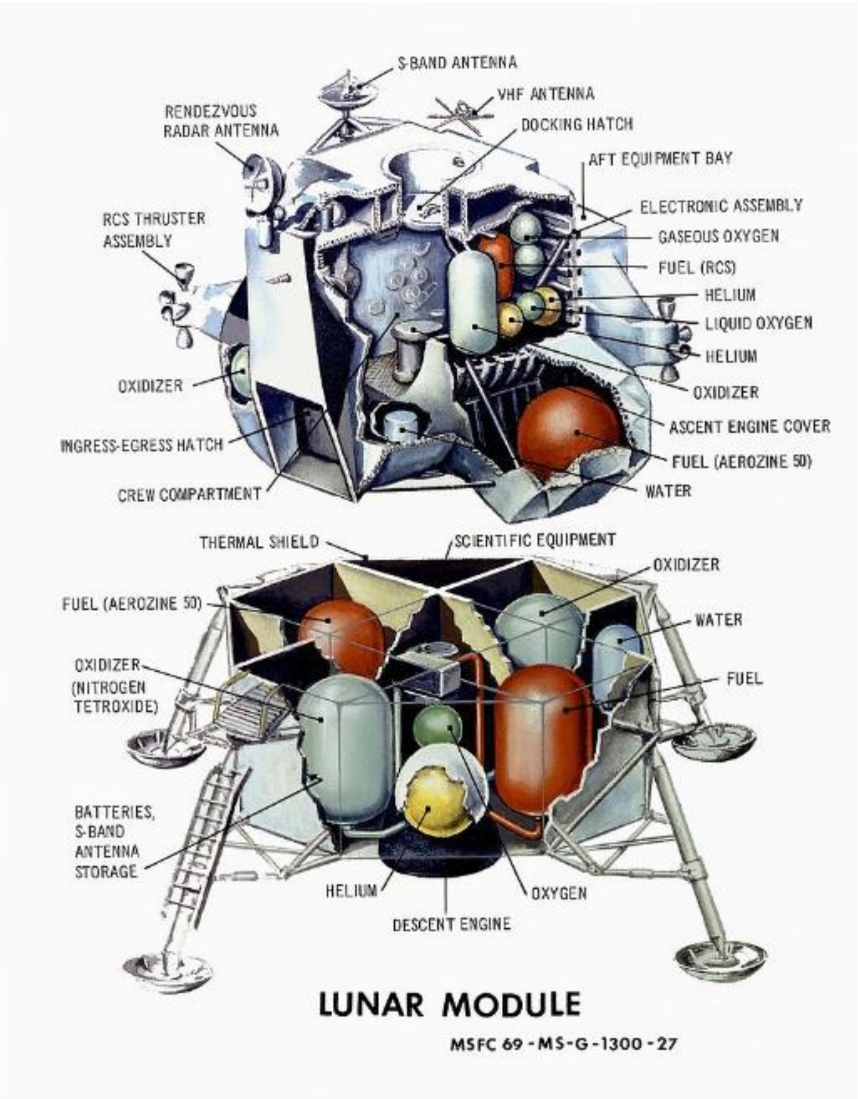

Figure 5. Cutaway of LM Configuration[34]

Part 2 – Systems Engineering Described

Systems Engineering is a unique discipline that not only requires precise technological expertise but also an integration of thought processes, methods, actions, and management.

Systems Thinking[35]

Systems Engineering requires the use of a specific perspective for each engineering project: **systems thinking.** This perspective is a logical thought process that analyzes the operational need for a system along with the potential concepts for the system.[36] Systems thinking is simply thinking critically about the problem at hand, and it is a good method for anyone, not just for Systems Engineers.[37] Note that this thought process is not only chronological but also requires much iteration defined by continuous planning, designing, testing, and refining.[38] Each of the elements of systems thinking provides information for the others. Thus, systems thinking both determines and follows various patterns.[39]

Purpose & Problem

The purpose and problem are the *reason* for the development of the system, and they must be clearly defined in collaboration with the customer, who commissions the development of the system.

Assumptions & View

Stating assumptions and viewpoints is one part of systems thinking is obvious when explicitly stated but can be easily overlooked. All assumptions must be stated, understood, and tested based on current information or simulated with knowledge of how the system is understood to behave.[40] Engineers *must* recognize their biases and assumptions and welcome and consider many different points of view in order to design an optimal system.[41]

In addition, the system must be viewed from multiple perspectives in order to discover how it will relate to and integrate in the real, diverse, dynamic world. This requires a multi-disciplinary viewpoint – or better, a multi-disciplinary team, each of whom can give his or her input and learn together. These diverse viewpoints help to define the system, which in turn helps to limit the number of views to consider.[42] Note that the system must still be viewed as a complete whole, even while shifting perspectives.[43]

Data & Concepts

Component attributes, dynamic behavior, and system interactions must be measured, and these measurements can be used to estimate the future behavior of the finished system, while taking the environment into account.[44] All assumptions and design decisions *must* be based on the actual data received.[45] Absolutely essential to the success of the project is understanding the current state of a system at every point in the development, continuing to monitor the important characteristics of the system as it is developed, and correcting anything that does not fall in line with the purpose.[46] The initial decisions about the function and scope of a system will greatly impact the final design; but the earlier the current state and potential of the system is understood, the easier it is to regroup and fix if a problem arises.[47] This is the part of system thinking in which most of the "real" engineering work is done – developing concepts, gathering data, and stating the interpretation of the data.

Conclusions & Implications

As with assumptions and design, all conclusions and further decisions require careful analysis based on the actual data and current state of the system.[48] The way to make an informed decision about a system is to gather the data, analyze it (making note of concepts and interpretations), and compare alternatives. Choose the best or optimal solution – perhaps even optimizing it further – that gives the greatest benefit to the customer through fulfilling the requirements and preferences as far as possible, with minimum cost and risk. [49]

The chosen design of any system will have implications, often including unintended consequences, for development and operation. All of these implications must be considered as they relate to the current state of the system (the actual data) and must include all known possible causes, effects, interactions, and consequences – even those not expected, which is where multiple viewpoints help again.[50] This analysis usually requires making changes to the system as designed or built. [51]

Example – Lunar Orbit Rendezvous[52]

The development of the Apollo **mission mode** – the plan for *how* men would fly to the moon, including the configuration of the spacecraft – demonstrates the wisdom of a few people who persisted in systems thinking, keeping their minds on the purpose and their eyes on the data and context. Eventually, NASA chose the **Lunar Orbit Rendezvous (LOR)** mission mode, which is detailed below.

Purpose & Problem – How Can We Win in Space?

Under the orbit of the Soviet Sputnik, the people of the U.S. felt the urgency of fear of political domination by another world power. Although their fears never came true, they provided extraordinary motivation for ordinary people to join in the effort.[53] In addition, the potential of doing something in space, something never done before, also united people through the possibility of advancement and through personal excitement.

The development of the mission mode depended fully on this purpose and problem. Initially, the purpose caused NASA to consider the manned lunar mission and eventually the lunar landing mission. From there, the problem was short and simple to state: get a man to the moon. The mission mode was more difficult: *how* to actually do it.

Assumptions & View – How do We Fly to the Moon?

At the beginning of the Apollo development, no one knew how to get to the moon. No one had ever done it before![54] Originally, NASA had only one perspective on the mission mode: They just assumed the spacecraft could fly straight from Earth to the moon with a single spacecraft, no orbits needed.[55] This was called the **Direct Descent** mission mode, and NASA simply assumed this mission up to May 1961.[56]

An unimpressive NASA engineer named John Houbolt brought forward the Lunar Orbit Rendezvous mission mode, which proposed a secondary lander spacecraft separating from the "mother ship" to land on the moon (with the astronauts) and then launching from the moon to rejoin the main spacecraft in lunar orbit. NASA did not like this idea at all at the beginning because it seemed incredibly risky – performing a completely new rendezvous maneuver and launch that far from Earth. However, everything was risky in space endeavors.

Houbolt persevered in stating his views, even in the face of blatant rejection. He did not have experience with orbital mechanics, which could be why came up with this new idea at which others initially scoffed.[57] In the face of blatant, unremitting criticism, Houbolt pointed out that the mission needed to be tailored to the current technological capabilities instead of to the imaginations of people who wanted something impressive. The point of the mission was to get to the moon before the Soviet Union – not to get there in a "flashy" way.[58] As long as the LOR worked, it would fulfill its purpose.

Figure 6 below shows the basic LOR plan in a sketch possibly done by John Houbolt himself.

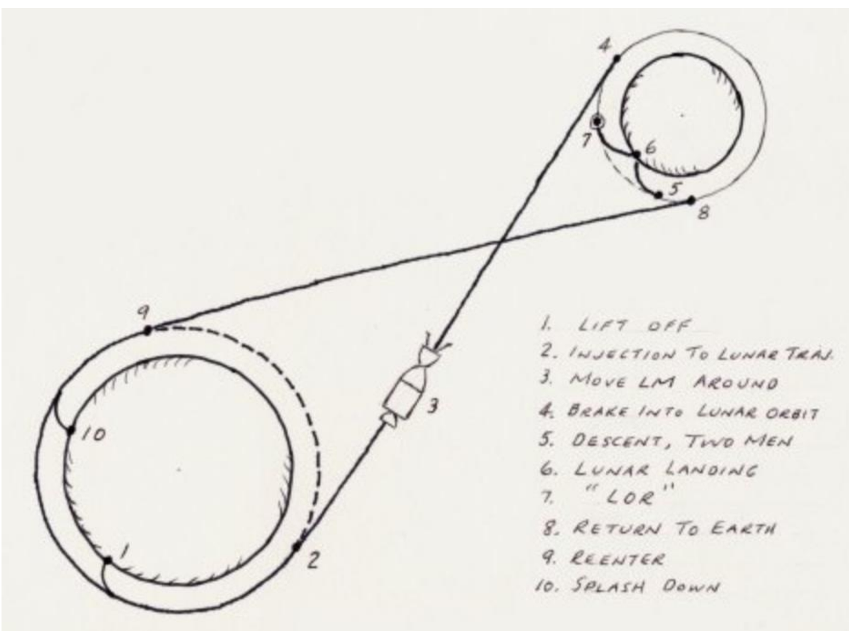

Figure 6. LOR Sketch[59]

Data & Concepts – Which Mission Mode is the Fastest?

While NASA was arguing about mission modes, Grumman had taken a costly step in choosing to continue internal studies on potential NASA space plans and to only explore options for a single mission mode: the LOR.[60] Sometime along the way, Grumman engineer Tom Kelly (who played a huge role in the development of the LM, including acting as chief engineer of the design and being called the "Father of the LM"[61]) realized the worth of John Houbolt's ideas and was perhaps the first person to take his ideas seriously.[62]

After performing the analysis, even though the rendezvous on the other side of the moon was apparently what concerned NASA so much, Grumman realized that the maneuver was not particularly difficult. In fact, they found many ways to do it successfully.[63] Kelly personally was concerned more about the launch from the moon – without any of the ground equipment and support needed for the full Apollo launch.[64]

In addition to their internal studies, Grumman was assigned to study the LOR for the **General Electric (GE)** proposal for the Command Module.[65] GE assigned to each of its four contractors (including Grumman) one mission mode to study, and GE decided upon the LOR due to Grumman's research.[66] Grumman apparently also realized that the NASA focus was slowly shifting to LOR, which encouraged them in their study; and Grumman presented their internal findings to NASA in December 1961.[67]

Eventually, NASA realized that the mass required for the direct method would prohibit that mission mode, and they began considering other options, assuming some variation of the **Earth Orbit Rendezvous (EOR)** mission mode by the end of 1961.[68]

The following table (Table 1) shows five of the considered mission modes, including the primary benefits and risks of each. Below the table, Figure 7 shows an example of one of the tradeoffs considered among the mission modes: the comparison of the spacecraft sizes for the direct method versus the LOR.

Table 1. Comparison of Possible Apollo Mission Modes[69]

Name	Description	Benefits	Risks
Direct Descent	Whole spacecraft separates from launch vehicle and flies to moon, lands, launches, and returns to Earth	➢ Simple ➢ No rendezvous in space ➢ Single mission	➢ Huge mass (estimated Earth weight 68 tons) ➢ Huge launch capacity of launch vehicle ➢ Did not take Earth/lunar orbits into account ➢ Required a spacecraft that was both an orbiter and a lander ➢ Problem in getting an astronaut from Lander in landing stack all the way down to the lunar surface ➢ Long time to develop
Earth Orbit Rendezvous (EOR)	Multiple launch vehicles send multiple small spacecraft into Earth orbit Spacecraft would then rendezvous and travel to the Moon (several variations on this idea)	➢ Required much less power (per spacecraft) than the direct method ➢ Easier to return home if failed ➢ Potential to keep a presence on the moon at all times (military purposes)	➢ Complex coordination of rendezvous and docking of multiple small vehicles ➢ Required greatest number of rockets ➢ Most complex method ➢ Did not take lunar orbit into account ➢ Long time to develop ➢ Many missions ➢ Huge mass of final spacecraft to land on moon
Lunar Orbit Rendezvous (LOR)	Deploy a smaller spacecraft down to the moon to land and then take off again to dock with orbiter	➢ Required only one Saturn V ➢ By far the best in terms of mass (only taking down to the surface what was absolutely required and leaving some things on the moon) ➢ Estimated to save $1.5M ➢ Ready in 6-8 months ➢ Simplified CSM by not having to make it capable of moon landing ➢ Single mission	➢ Rendezvous maneuver in lunar orbit, far from Earth ground station (biggest risk) ➢ Design of a second spacecraft (second biggest risk) ➢ Takeoff from the moon (worked or did not)

Lunar Surface Rendezvous	Send many small vehicles to the moon, some with the return vehicle, supplies, propellant, etc. and send the astronaut last	➢ Prepare everything on the moon before sending a human (safety) ➢ Smaller launch vehicles ➢ No rendezvous in space	➢ Many missions ➢ Robotics needed to work on the Moon in the absence of humans ➢ Long time to develop (especially robotics)
One-way Mission	Send an astronaut to the moon and keep him alive by sending supplies until engineers could figure out the way to get him back	➢ Get an American to the moon before the Soviet Union ➢ No rendezvous in space	➢ No comment.

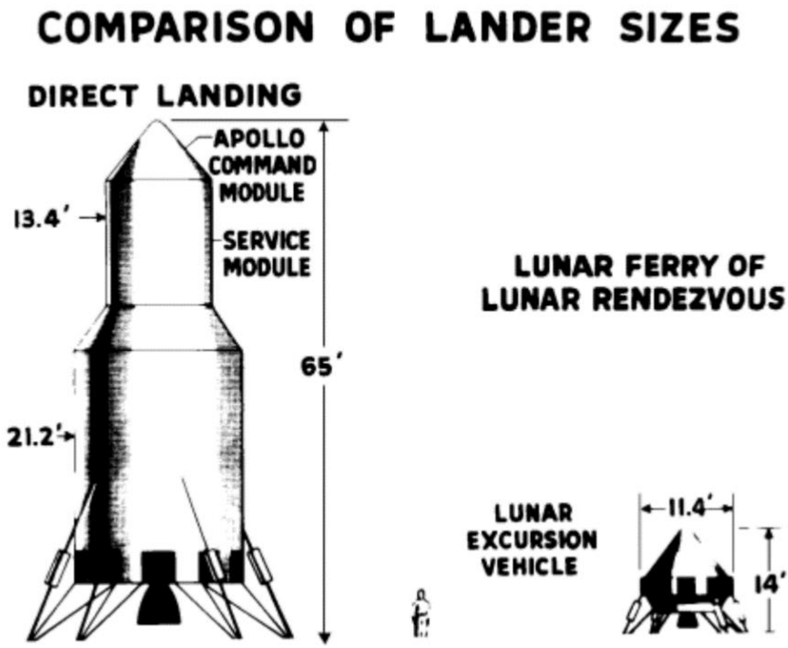

Figure 7. Comparison of Direct vs. LOR Lander Sizes[70]

Conclusions & Implications – What Mission Mode Should We Choose?

In May 1962, NASA began paying attention to Hoboult's ideas, perhaps as a last resort or because of Hoboult's annoying persistence. The turning point for NASA came in June when Wernher von Braun (the developer of the Saturn V rocket series and primary proponent of the EOR, which would have greatly benefited the rocket manufacturers in Huntsville, Alabama) announced that he supported LOR. He was the first primary decision-maker who realized the potential of the LOR, and his personal change of mind seemed to change NASA's plans.[71] NASA chose the LOR in July 1962, in part due to Von Braun's decision and NASA's and Grumman's internal research.[72] However, the real driver for the decision was Kennedy's schedule restraint: get to the moon by the end of the 1960s.[73]

On the 7th of November, NASA announced the winner of the LM proposal: Grumman.[74] They were likely chosen to develop the LM because of their prior research on the LOR.[75]

System Life Cycle[76]

As noted before, the system life cycle extends from the idea or need for a system through the design, integration, testing, operations, and retirement. In a sense, Systems Engineering takes apart an idea into the conceptual components of a design and then builds them back together into an actual system.[77] SE defines the purpose, problem, requirements, plan, and finally the design for a better final product.[78]

The development of a system consists of four main activities: (1) **management**, (2) **design**, and (3) **production**, and (4) **operation**.[79]

Management

In a SE context, the **Project Manager (PM)** sets the tone for the project and for the team. The manager must make sure that the customer and technical requirements, performance, cost, schedule, and so on are controlled. In addition, the manager must also organize the team to best work on the project and must interact with the stakeholders to determine what their desires are and how to design the system to best fulfill those desires.[80] These management activities happen across the entire **system development process.**

Teams

In today's engineering world, no project is composed of a single engineer working alone. All projects include both a leader and a team – often several of both.[81] As a true leader, the project manager must provide clarity, guidance, organization, conflict resolution (both technically and socially), motivation, and vision for the project.[82] The manager is responsible to lead the team ethically in the workforce to fulfill the customer's desires while protecting integrity.[83] In addition, a good leader remembers that the whole team is simply ordinary people working together for a common goal.[84] Leadership is a difficult task due to managing people, let alone leading them to develop a complicated system![85]

Planning

Cost, risk, quality, performance, and schedule are all related to each other and must be considered together to determine how they affect one another.[86] In addition, the farther a team has gotten into a project, the greater the cost of making changes will be because the extent of the commitment of time, money, and resources is also greater.[87] Thus, a project schedule is generally broken down into various stages, separated by major reviews and many other such checks. At each review, the team and the customer must decide, based on the planned status and actual status of the project, which of the following four actions to choose:[88]

1) *Go* – continue the project as planned or modify the plan
2) *Recycle* – redo part or all of previous work
3) *Hold* – pause the project until more resources arrive or a better or different demand for the product arises
4) *Kill* – stop the project because it is no longer profitable

Verification & Validation

Throughout the system development phases, the team continually determines whether or not the system will meet its requirements (**verification**) and fulfill its purpose (**validation**). These two critical, continual checks are done especially thoroughly before the system is delivered to the customer.

Documentation & Configuration Management

If a component, process, plan, set of analysis data, and so on was not documented, then for all intents and purposes, it didn't happen.[89] Documentation is essential across the whole project life cycle in order to demonstrate what work was actually done and to document changes made to each successive plan. **Configuration Management (CM)** documents all changes to the design and the system to ensure that the components will work together correctly. The following are some examples of such documents:[90]

- **Request for Proposal (RFP)**
- **Proposal**
- **Statement of Work (SOW)**
- **Systems Engineering Management Plan (SEMP)**
- **Concept of Operations (CONOPS)**
- **Project Master Plan**
- **Work Breakdown Structure (WBS)**
- **Integrated Master Plan, Schedule (IMP/IMS)**
- **Responsibility Assignment Matrix (RAM)**
- **Work packages**
- **Requirements Specification**
- **Interface Control Document (ICD)**

Because of the difficulty in communicating the purpose of a system and managing a project across many documents that all reference each other, the SE field is currently transitioning from documentation to **Model-Based Systems Engineering (MBSE).** This methodology seeks to organize a project into a conceptual model of the system, including graphical, mathematical, and logical representations of the model and documentation where necessary. MBSE integrates all parts of the design – from functions to performance to structure – to ensure easy **traceability** across the project. Then the engineer can look at the model see quickly which parts of the design a single change will affect without having to search for and through documentation. However, creating and maintaining the model requires careful attention and planning. In fact, the process of organizing a project using MBSE reflects the process of developing of the system itself.[91]

Design

The following stages of **design** describe in simplified terms how a system is developed.

Conception

The idea for the project reflects the purpose and problem, which are fully defined later as part of the system definition. The conceptual system must respond to a human need in the physical and, with today's technologies, in the cyber worlds.[92] **Conception** may begin with a desire of the customers or with an idea of engineers for which they can find customers.[93]

Customer Requirements

Customers and stakeholders always want a product that will fulfill their purpose and expectations at the lowest cost, with the highest quality, and as soon as possible.[94] Because the system must fulfill the purpose as defined by the customer, the engineers must define who the customers and stakeholders are, correspond with them, fully explore and document their desires at the beginning of the system development process, and understand how well a design can fulfill the customer desires while still being profitable for the engineering organization.[95] In other words, the configuration of the system – even before that, the technical requirements for the system – *cannot* be determined until the purpose, mission, and functions of the system are understood.

Unfortunately, customers may find it difficult to articulate their expectations, or they choose not to do so in order to see what the engineers can create. Thus, the team must work hard to determine what the customers actually want. In addition, communication must continue to ensure that the design and implementation of the system correctly interprets the customers' (often changing) preferences.[96] The Kano model of **customer requirements** describes three types of customer requirements:[97]

1) *Basic* – assumed by the customer to be present in the design (still need to be defined by the team)
2) *Performance* – stated by the customer
3) *Excitement* – not expected by the customer but do increase the value of the produced system and enhance the reputation of the engineering company

Technical Requirements

These are the "system shall do X" statements for the actual system to be built and are defined during the design phase.[98] They depend on the planned functions of the system to be built – which requires defining the essential characteristics of the system (necessary to fulfill the purpose), other requirements needed to support the main ones, and risks associated with the requirements and purpose.[99] These requirements define the actual problem to be solved from a technical perspective, and they are followed in the design and checked against the system performance in verification.[100] All **technical requirements** (and any other defined non-technical requirements) must be necessary. Non-essential requirements will impose artificial constraints.[101] They must also be measurable so that they can be continually tracked, monitored, and checked against the design.[102] Such measurements are defined in the following four categories:[103]

1) **Measure of Effectiveness (MOE)** – defines how well the system fulfills the mission
2) **Measure of Performance (MOP)** – demonstrates the system performance or functions and how well it fulfills the customer requirements
3) **Key Performance Parameter (KPP)** – the most important measurements of system attributes, directly influencing the success of the system in achieving the purpose
4) **Technical Performance Measure (TPM**) – other technical measurements that are tracked against the technical requirements

For example, in an Aerospace context, mass is an important TPM (or even a KPP); for it can be measured, and it directly affects the performance of the aircraft being designed.[104]

System Design

The design *must* begin with the purpose that the customer has in mind and *must* include considerations of the environment in which the technical artifact will operate.[105]

The design process begins with research on various current systems and ideas before and during requirements definition. These activities progress into more and more detailed design and models to verify that the appropriate design (or designs) are being considered for the conditions and requirements of the project. This process requires breaking down the system into levels of subsystems and individual components in order to understand the parts that make up the whole, while also considering how they interact with one another.[106] Requirements are developed for each level of the system.

As an illustration, Figure 8 below shows a *very* simplified breakdown of the Apollo 11 system.

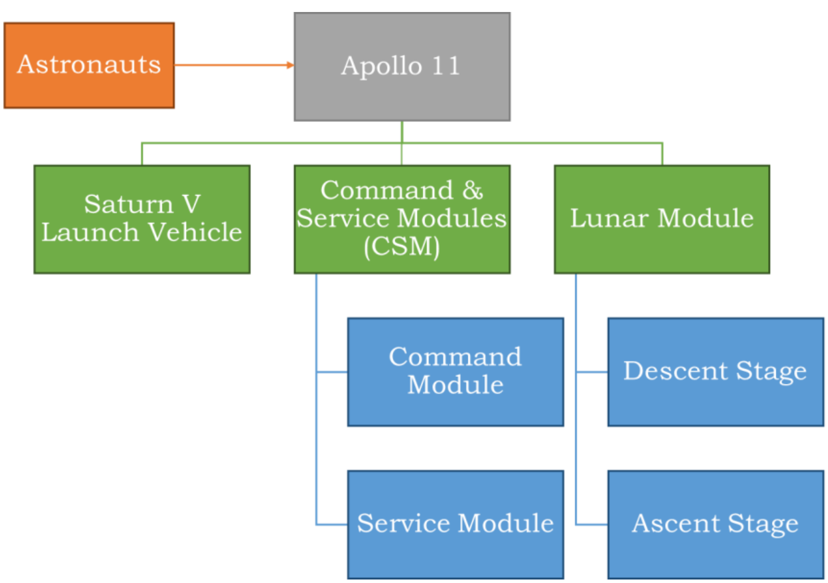

Figure 8. Simplified Apollo 11 System Architecture

Finally, the team chooses the best design, defined by specific technical requirements and analysis of the interactions among the parts of the system, designed with cost, schedule, risk, and quality in mind.[107] At this point, most of the planning for the project is completed.[108] The design must be defined fully and carefully, in preparation for integration in the production phase, though the design is further refined during integration and testing.[109]

Note that the design process is iterative, even while progressing from basic ideas and concepts through preliminary design to final design to production and testing – a continual cycle of checking against the purpose, problem, and requirements.[110]

Production

During this phase of the life cycle, the system is actually built, assembled, tested, and delivered to the customer.

Integration & Testing

The hardware and software are either bought or built and tested separately, and finally they are integrated and tested yet again.[111] Integration is the hardest part of the system life cycle, in part because there are no rules for how it should be done.[112] It can be planned for very carefully, but no planner is all-knowing, and many unforeseen circumstances occur while combining components that are usually produced by many different suppliers for different purposes.

The testing during integration ensures that the system was designed and built correctly for customer use. The operators must be able to use it to its intended capability with minimal training and troubleshooting.[113] Here, verification and validation are vital to make sure that the product meets the customer requirements and purpose.[114] This process also includes preparing for the transition from the product currently in use to the new system, making sure that the customer can receive the system smoothly and effectively.[115]

Delivery

Finally, the system is completed and delivered to the customer, along with all the required documentation (such as troubleshooting and training guides, test data, requirements specifications, and so on, based on what the customer requested). The delivery ends the system development process.

Operation

Now the customer can use the system, but the work is not completed. Here, the quality of the work is determined in the actual use by the customer – whether or not the system fulfills the purpose for which it was produced.[116]

Maintenance & Updates

The operation phase requires upkeep and troubleshooting on the system and often includes incremental updates, in order to match its dynamic environment.[117]

Retirement

This is the disposal of a system, when its purpose is completed, it fails to perform, it needs to be fully updated, or it is replaced. Retirement too requires a plan for removing and replacing the system without a disruption of operation and through a safe disposal process.[118]

The following table (Table 2) illustrates the various stages of system development, including the definition of a system, systems thinking, and the system life cycle. Note that the elements of each are placed where they "happen" chronologically, though they all should be considered throughout the process.

Table 2. Summary of System Development[119]

<table>
<tr><td rowspan="2">System Definition</td><td colspan="6">Environment</td></tr>
<tr><td colspan="3">Purpose
Problem</td><td colspan="3">Behavior
Attributes</td></tr>
<tr><td>Systems Thinking</td><td colspan="3">Purpose
Problem</td><td colspan="3">Assumptions
Perspectives
Data, Concepts, Conclusions</td></tr>
<tr><td rowspan="4">System Life Cycle</td><td colspan="6">Management</td></tr>
<tr><td colspan="6">Planning, Teams, Documentation, Configuration Management (CM)</td></tr>
<tr><td colspan="6">Design</td></tr>
<tr><td>Conception</td><td>Research</td><td>Customer Requirements</td><td>Technical Requirements</td><td>Preliminary Design</td><td>Chosen Design</td></tr>
</table>

<table>
<tr><td rowspan="2">System Definition</td><td colspan="8">Environment</td></tr>
<tr><td>Components</td><td colspan="3">Integration
Interfaces</td><td colspan="4">Behavior</td></tr>
<tr><td>Systems Thinking</td><td colspan="5">Data
Conclusions</td><td colspan="3">Implications</td></tr>
<tr><td rowspan="4">System Life Cycle</td><td colspan="8">Management</td></tr>
<tr><td colspan="8">Teams, Documentation, Configuration Management (CM)</td></tr>
<tr><td colspan="5">Production</td><td colspan="3">Operation</td></tr>
<tr><td>Components & Testing</td><td>Integration</td><td>System Testing</td><td>Final Verification & Validation</td><td>Delivery Transition</td><td>Use</td><td>Maintenance & Updates</td><td>Retirement</td></tr>
</table>

Example – Apollo Design Reference Mission

Because of the fight within NASA over the mission mode, Grumman was chosen to build the Lunar Module (LM) a year after **North American Aviation (NAA)** won the contract for the Command & Service Modules (CSM). In addition, Grumman soon realized that even with the Lunar Orbit Rendezvous (LOR) mission mode, the mission was not anywhere near being fully defined. All of these circumstances contributed to Grumman working far behind schedule until late 1968 – and to Grumman taking the initiative to fully define the mission.

The design of the LM spacecraft was bound up with the LOR, and Grumman studied both together, which pointed to the need for the "design" of the *mission* before the design of the spacecraft structure.[120] Although NASA stated that systems integration would bind the whole project together,[121] they did not provide very specific instructions. Nevertheless, Grumman knew that an understanding of the mission would pave the way for determining how the LM would be designed and integrated with the rest of the Apollo spacecraft. [122]

Concept of Operations

Grumman knew they must integrate the purpose and mission from the users and stakeholders (NASA and the people and political leaders of the U.S.) with the implied functions and then define requirements and actual hardware from there.

After winning the LM proposal, the Grumman team realized that they needed a more carefully-defined mission for the whole Apollo project. They discussed the situation with NASA, and NASA realized that they did not have a "reference mission" against which to design the spacecraft and supporting equipment. Thus, in 1964, Grumman created the **Design Reference Mission (DRM),** which elaborated upon the current LOR plans and determined the mission objectives as well as every single step of the mission,[123] along with potential failures and contingencies, including the all-important rendezvous procedure.[124]

Grumman defined the basic Apollo mission objectives: Two astronauts needed to land on the moon, gather scientific data and lunar material, and return to Earth safely. [125]

The DRM working group chose May 6, 1968 as the projected launch date and worked backwards from there. They planned every single operation and action of the astronauts and the other crew. They determined all contingencies of flight operations and documented all mitigation plans. After four months of work, the team produced the completed DRM, ready to be refined as the design progress continued. Each of the contractors then better understood *what* they needed to do – the first, most important step in getting to *how* to do it.[126]

Interestingly, the DRM failure and mitigation modes included the original "lifeboat" studies for the LM, which were used unexpectedly several years later in the rescue of the Apollo 13 crew.[127]

Requirements Definition

Even after Grumman won the proposal for the LM (November 1962), they had to meet with NASA personnel in order to define the scope of the work before Grumman could be officially under contract. In fact, the proposal was more about measuring competency and knowledge, rather than defining an optimal design solution.[128] NASA would not simply buy Grumman's design but would work with them to refine their work.[129]

NASA had given very few and very general high-level requirements and no requirements specifications.[130] No one at Grumman really knew what NASA wanted, and they had just finished and won the proposal![131] Grumman then had to rework their design, and because the LM was already late due to debate about the mission mode, Grumman drove the schedule (was the **critical path**) for the Apollo program.[132]

Grumman mitigated this lack of understanding of the project scope through communication with NASA, the foresighted study of the LOR, and the development of the DRM. Grumman planned for six months of rework after the proposal, which included new requirements from NASA, the other contractors, and the scientific community – as well as many requirements added simply because of NASA uncertainty.[133] In fact, the only part of the Grumman proposal that remained after the rework was the basic concept of the two-stage vehicle.[134]

For defining the requirements, Grumman followed a careful SE process that was new to them: They started with the DRM and used it to define the Apollo mission, which they then broken down, layer by layer, into the corresponding requirements for each subsystem and component. At the lower layers, they could form drawings and procure parts. Grumman defined the top layer (level 1) as the full LM spacecraft and broke the whole system down to level 6, with corresponding drawings that showed all of the system components, interfaces, and interactions.[135] Grumman made sure to compare the text and implied requirements of the DRM with the actual stated requirements specifications for the LM.[136]

Along the way, Grumman had to make **tradeoffs** – decisions to decrease quality or performance in one area in order to increase it in another, within the constraints of the customer, design, and environment. For example, they chose to never compromise safety, gave very little ground on reliability, and decreased maintainability instead.[137]

Thus, Grumman originally designed the LM with basic requirements from NASA, alongside their own internal study of the LOR. Yet, when Grumman actually won the contract for the LM, they wisely took the initiative to define the full mission and its derived requirements.

Figure 9 below shows the Apollo spacecraft in the launch configuration.

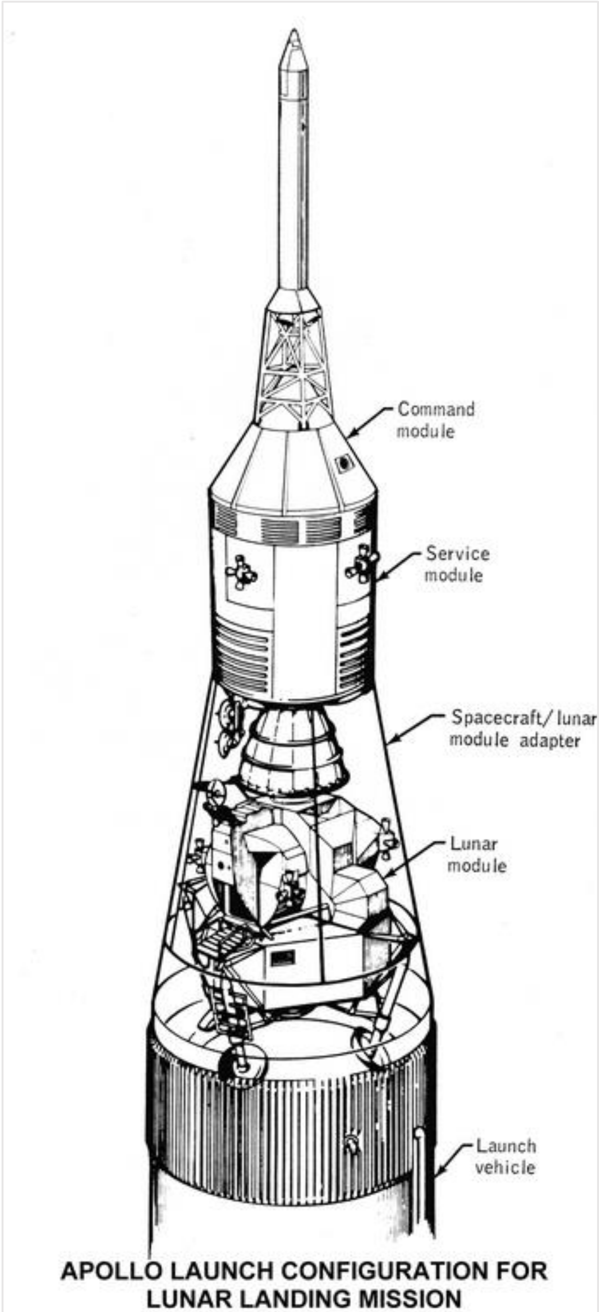

Figure 9. Apollo Launch Configuration[138]

Part 3 – Systems Engineering Performed

Systems Engineering is becoming an essential part of the engineering world today, and it provides much useful experience and many promising career paths in all of the phases of the SE life cycle.

Mindset

Systems Engineering does not simply rely on technical, mathematic, and scientific knowledge. It requires application of knowledge in many subjective areas with no definite “rules” – combining knowledge from engineering, humanities, and the culture in general.[139] Systems engineers (**SEs**) cannot just know their specialty and expect to form a completely successful product. They must see the system as a whole, fulfilling the mission and the desire of the customer within the project team.[140] SE is intriguing because of the challenge of integrating the purpose, customer and technical requirements, design, components, interactions, schedule, and so on. SEs must know their customer, the environment in which the customer will use the system, and the consequences or implications of the use of the system.[141]

SEs are analytical and innovative, enjoy learning, engage in problem-solving, meet challenges, seek to verify assumptions, possess a strong technical foundation in multiple areas, consider many alternatives and factors at once, and exercise communication and leadership abilities.[142]

Tasks

SEs envision a system that fulfills the customer’s desire throughout the entire life cycle of the system and lead in the development of that system.[143] SEs help determine the system definition, requirements, planning, verification, cost, tradeoffs, risk, and documentation.[144] Because systems are complicated and have so many interactions inside and outside, SEs have to focus on managing risk in order to estimate how a system will behave and address potential or actual issues.[145]

In addition, SEs must also interact with many kinds of stakeholders.[146] Also, projects require diverse teams in order to incorporate varying perspectives.[147] Thus, SEs must work with all kinds of people within the project context.

Career Paths

Because Systems Engineering is so diverse, requiring both a firm foundation in technical *and* social skills, a career in this field includes many opportunities for working and learning. “Moving up” in the SE workforce is accomplished by a combination of experience (the most important factor), mentorship, thinking, and training.[148] SEs should seek opportunities for new challenges in order to learn and grow in their careers.[149]

Further breakdown of SE careers mirrors the system life cycle. In other words, SEs can choose to focus on one part or task in the cycle that interests them,[150] or they can choose to start with a project and see it through much of the life cycle.

Although experts in each area are essential, SEs who possesses knowledge and skills across many different areas are particularly valuable, especially in a context in which a wide perspective is necessary.[151] This ability to work in all kinds of situations may be the greatest strength of SEs.

Table 3 below lists a few SE tasks organized by system life cycle.

Table 3. Systems Engineering Tasks[152]

Management	Design	Production	Operation
Management	Requirements Definition	Procurement	Training
Schedule	Research	Installation	Maintenance
Cost	Incremental Design	Inspection	Trouble-shooting
Risk	Modeling & Simulation	Testing	Disposal
Quality	Technical specialization	Verification Validation	
Configuration Management			
Technical Writing			
Customer Interface			

Example – Grumman Engineers

Especially at the beginning of the Apollo project, NASA did not set a clear idea of how the mission was to be performed, wanting the contractors to figure out how to do it. This perspective is understandable, given the huge technological opportunities and political pressure, but it made the design and development difficult for the contractors who didn't know what they were building. In the end, after many twists and turns, Grumman's hard work in planning for the mission and developing the Lunar Module paid off: On July 20, 1969, Apollo 11 completed the mission chosen by NASA.[153]

Although Grumman had a difficult time with many aspects of the LM program, they kept their eyes on the purpose the whole time, using that as the basis for defining the mission, requirements, and configuration. This is, in fact, the way to design systems – determine the customer's purpose, define the functions required to fulfill that purpose, and *then* determine what structure best fulfills that purpose.[154] In this, they set a good example for Systems Engineering for all kinds of projects: All projects *must* focus on understanding the customer need and build outwards from there. Thus, the LM not only gave us a revolution in scientific worldview but also a stellar (pun not intended) example at the mission level in a new engineering discipline that is still being explored today for the potential it provides to the engineering world.[155]

Figure 10 below shows Grumman engineer Tom Kelly during the Apollo 11 mission, and Table 4 shows the experience of the Grumman engineers in space-related projects before the LM.

Figure 10. Tom Kelly During the Apollo 11 Mission[156]

Table 4. Grumman's Space Work up to the LM[157]

Task	Description	Result	Date
Studying NASA's plans	Internal study preparing when NASA was potentially choosing to send men to the moon	-	Started in about 1958
Mercury	Simple and imaginative design	Lost due to NASA's concern about Grumman having too many large contracts already (after initially choosing Grumman design)	Jan 1959
Orbiting Astronomical Observatory (OAO)	Telescope before Hubble Space Telescope	Won, by a long shot Gained a place in the space world for Grumman	1960
Launch & Landing Trajectory	Results of internal Grumman study Knew that NASA was considering manned moon landing	Lost Continued on Grumman's funds	Oct 1960
Mission Feasibility Study	Continuation with Grumman funds Presented to NASA after NASA-funded competition		May 1961
Command Module	Grumman management chose to join a larger contractor to keep from "betting" the whole company, although engineers thought Grumman had the full potential to build what was required Decided on LOR as part of proposal process	Lost to North American Aviation (NAA), possibly due to a too complex team	Nov 1961
Study of LOR (and LM)	Developed LOR approach from GE proposal Presented to NASA and compared with NASA's design (similar)	Lost competition for NASA funding to Convair Continued using company funds NASA ended up choosing LOR as the Apollo mission mode	Dec 1961 - June 1962
Lunar Module (LM)	Full development phase Unusual RFP – focused on company knowledge and potential instead of on exact design, since the winner would work alongside NASA Already had feedback from NASA NAA was required to integrate LM with CSM and Saturn V	Won NASA complemented Grumman knowledge and ingenuity in some areas and warned of over-simplification in others.	Nov 1962 March 1963 (contract)

Part 4 – Systems Engineering at UAH

Systems Engineering is promoted at **The University of Alabama in Huntsville (UAH)** within the **Industrial & Systems Engineering and Engineering Management (ISEEM)** department. The department offers a Bachelor of Science in Industrial & Systems Engineering and multiple options for graduate students. However, the faculty are currently working to create an undergraduate degree in Systems Engineering. For more information, contact one of the faculty members listed below.

Figure 11. UAH ISEEM Logo

ISEEM Faculty

Figure 12 below lists the ISEEM faculty at UAH, along with their specialties. Some focus on Systems Engineering (SE), while others cover **Industrial Engineering (IE).**

Professor	Specialty
Dr. Paul Collopy	SE, economics
Dr. Sampson Gholston	IE, lean six sigma quality
Dr. Bryan Mesmer	SE, operations research, gamification
Dr. Sherri Messimer	IE, production & manufacturing processes
Dr. Leonard Petnga	SE, systems modeling
Dr. James Swain (department chair)	ISE, probability & statistics, simulation
Dr. L. Dale Thomas	SE, space

Figure 12. UAH ISEEM Faculty[158]

ISE Classes

Below is a table listing the undergraduate ISE classes currently required in the undergraduate ISE degree and the Systems Engineering electives. See the UAH course catalog for more details.

Table 5. ISE Classes[159]

Number	Title	Topic
ISE 224	Introduction to Industrial & Systems Engineering	ISE
ISE 321	Engineering Economy	Engineering Economics
ISE 324	Work Design	Lean Manufacturing
ISE 327	Management Systems Analysis	SE
ISE 340	Operations Research	Optimization
ISE 390	Probability & Engineering Statistics 1	Statistics
ISE 391	Probability & Engineering Statistics 2	Statistics
ISE 423	Introduction to Statistical Quality Control	Six Sigma Quality
ISE 428	Systems Analysis & Design 1	Senior Design
ISE 429	Systems Analysis & Design 2	Senior Design
ISE 430	Manufacturing Systems & Facilities Design	Manufacturing Systems
ISE 433	Production & Inventory Control Systems	Inventory Control
ISE 439	Special Topic Electives: Introduction to Systems Systems Engineering Modeling	SE MBSE
ISE 447	Introduction to Systems Simulation	Simulation

Glossary & Acronyms

Note that all definitions and descriptions are with respect to the context in which the terms and acronyms are used (e.g. Systems Engineering, the Apollo Lunar Module, etc.)[160]

A	**Attribute**	A measurable characteristic of a component or a system that helps to define how it behaves
B	**Behavior**	How the components or system "act"
C	**CDR**	Critical Design Review
	CM	Configuration Management
	Command Module	The part of the Apollo spacecraft for the astronauts, in which they returned to earth
	Component	An object chosen, created, or engineered for one or more specific purposes and needs
	Concept of Operations (CONOPS)	Defines high level matters (organization, objectives, procedures, reviews, etc.) at the beginning of a project and manages whole project from an SE perspective of the mission that the system needs to perform
	Conception	The idea for a system, the customer's realization of a need or desire
	Configuration Management (CM)	Keeps track of all parts and interactions within a system and makes sure that they will still work together with the iterative changes in development
	CONOPS	Concept of Operations

	Critical Path	The sequence of actions on a program that takes the longest time when done immediately in order, which drives the schedule of the project
	CSM	Command and Service Modules
	Customer	The person, persons, or organization that commissions the development of the system and defines the purpose and problem to be addressed
	Customer Requirements	What defines the customer's need or desire; developed with the organization that develops the system
D	**Design**	The process of taking customer desires and translating them into a clearly defined conceptual model (usually partially concrete as well) that best fulfills those desires under the necessary constraints
	Design Reference Mission (DRM)	Concept of Operations for the whole Apollo mission, created by Grumman in order to define functions to point to requirements
	Direct Descent	The idea that the Apollo spacecraft could simply fly directly to the moon
	DRM	Design Reference Mission
E	**Earth Orbit Rendezvous (EOR)**	Mission mode with many variations involving multiple launch vehicles launching spacecraft that joined in earth orbit and flew to the moon
	Emergent Behavior	Behavior of the system that happens because of the specific, complex combination of components

	Engineering	A process of creating or manipulating components to fulfill a need of a person or group of people
	Environment	Anything outside the system, particularly what affects the system or interacts with it directly or indirectly
	EOR	Earth Orbit Rendezvous
F		
G	**GE**	General Electric
	General Electric	Prime contractor on Grumman Command Module work, which they lost
	Grumman Corporation	The company that designed and built the Apollo LM
H		
I	**ICD**	Interface Control Document
	IE	Industrial Engineering
	IMP	Integrated Master Plan
	IMS	Integrated Master Schedule
	Industrial Engineering	A field of engineering that focuses on improving processes by reducing waste
	Industrial & Systems Engineering (ISE)	Undergraduate degree program at UAH
	Industrial & Systems Engineering and	Department and graduate degree program at UAH

	Engineering Management (ISEEM)	
	Integrated Master Plan (IMP)	Shows the general timeline of the project, highlighting the major reviews
	Integrated Master Schedule (IMS)	Detailed description of how the team will develop the project to completion relative to time
	Integration	Combining all technical components, including evaluating their interactions, to form a complete system
	Interface	The point of interaction between components in a system
	Interface Control Document (ICD)	Describes planned interactions of system
	ISE	Industrial & Systems Engineering
	ISEEM	Industrial & Systems Engineering and Engineering Management
J		
K	**Key Performance Parameter (KPP)**	Important measurements that must be tracked closely to keep the system within requirements and to make sure it will fulfill the purpose
	KPP	Key Performance Parameter
L	**LM**	Lunar Module
	LOR	Lunar Orbit Rendezvous

Lunar Module (LM)	Spacecraft designed to fly from the main Apollo spacecraft to the moon
Lunar Orbit Rendezvous (LOR)	Apollo mission mode that had a second spacecraft (LM) detach from the rest of the spacecraft (CSM), land on the moon, and return to the CSM

M

Management	Oversight, organization, and planning of a project, technical and social
Massachusetts Institute of Technology (MIT)	MIT Instrumentation Laboratory was responsible for Apollo spacecraft guidance and navigation
MBSE	Model-Based Systems Engineering
Measure of Effectiveness (MOE)	Reflects how well the system will fulfill the purpose
Measure of Performance (MOP)	Reflects the system performance and functions
Mission Mode	The plan of how to get to the moon and what spacecraft configuration to use in order to get to the moon in that way
MIT	Massachusetts Institute of Technology
Model-Based Systems Engineering (MBSE)	A methodology for organizing the design of a project by forming a conceptual model of the system and integrating all the design information with the model
MOE	Measure of Effectiveness
MOP	Measure of Performance
NAA	North American Aviation

N

NASA	National Aeronautics and Space Administration
National Aeronautics and Space Administration (NASA)	Commissioned Apollo project
North American Aviation (NAA)	Company that won CSM proposal against GE and Grumman

O

OAO	Orbiting Astronomical Observatory
Office of Manned Space Flight (OMSF)	NASA office
OMSF	Office of Manned Space Flight
Operation	The activities involved with using a system – what the system is built for
Operator	Anyone who actually uses the system
Orbiting Astronomical Observatory (OAO)	Precursor to Hubble Space Telescope; proposal won by Grumman

P

PM	Project Manager
Problem	The human need that a system fulfills, which accompanies the purpose
Production	Actually "putting together" the components of a system based on the design for the customer's use, including testing and needed design changes; the focus of Industrial Engineering

Project Manager (PM)	The specific person (or persons) who perform the management roles in the design and production of a system
Project Master Plan	Describes the purpose of the project and how it will be conducted overall
Proposal	A document detailing an organization's plan to develop a system, often in an attempt to win a contract
Purpose	The reason that a system is built, the "customer's desire"

Q

R

RAM	Responsibility Assignment Matrix
Request for Proposal (RFP)	A document sent out by the customer detailing the system to be developed and initiating competition for the paid contract
Requirements	Statements developed throughout the system development process; state what the system or component in question "shall" do in order to fulfill the customer desire
Requirements Decomposition	Using requirements from a higher level and refining to define a lower-level component
Requirements Specification	A document listing the requirements for a specific system or component
Responsibility Assignment Matrix (RAM)	Shows who (which contractor or organization) has responsibility for each element of the project development process
RFP	Request for Proposal

S

SE	Systems Engineering
SEMP	Systems Engineering & Management Plan
Service Module	Part of the Apollo spacecraft that supported Lunar and Command Modules in orbit
SEs	Systems Engineers
SOW	Statement of Work
Stakeholder	Anyone who directly or indirectly affects or holds an interest in the creation and success of a system
Statement of Work (SOW)	Describes the work to be done on a specific project
Super Weight Improvement Program (SWIP)	Program implemented by Grumman to decrease LM weight
SWIP	Super Weight Improvement Program
System	A set of technical parts that are integrated to make a whole that fulfills a defined purpose or fixes a specific problem
System Development Process	Defined for this guide as the section of the life cycle including all design and testing up to delivery of the finished system to the customer
System Life Cycle	The "life" of a system, from conception to disposal
Systems Engineering (SE)	A field of engineering that works to integrate all the components of a system, focusing on the overall picture

		of how the system will interact with its users and environment
	Systems Engineering & Management Plan (SEMP)	Defines work for developing a system, along with requirements, schedule, responsibilities, and so on
	Systems Thinking	A critical-thinking viewpoint that seeks to fully understand the purpose of a system and to build all assumptions and design off of that, in accordance with the systems life cycle and environment
T	**Technical Performance Measures (TPM)**	Specific technical measurements of the system
	Technical Requirements	The requirements that constrain and define the system to be built
	TPM	Technical Performance Measure
	Traceability	The ability to see how all parts of a design relate to and influence each other
	Tradeoff	A choice of alternatives that decrease capability in one area in order to increase it in another due to the design constraints
U	**UAH**	The University of Alabama in Huntsville
V	**Validation**	Shows that the system fulfills customer's desire and the purpose for the project
	Verification	Shows that the system meets the technical requirements

W

WBS	Work Breakdown Structure
Work Breakdown Structure (WBS)	A hierarchical chart that describes the breakdown of a system during the whole development process
Work Packages	Describes the required work for each contractor or organization, including budget and other considerations

X

Y

Z

References

The works in **bold** are those that the author highly recommends for additional information about Systems Engineering and the Apollo Lunar Module.

Allday, Jonathan. *Apollo in Perspective: Spaceflight Then and Now.* Philadelphia, PA: Institute of Physics Publishing, 2000. Print.

Buede, Dennis M. *The Engineering Design of Systems: Models and Methods.* 2nd ed. Hoboken, NJ: John Wiley & Sons, 2009. Web. 02 Nov 2017.

De Weck, Oliver L., Daniel Roos, Christopher L. Magee. *Engineering Systems: Meeting Human Needs in a Complex Technological World.* Cambridge, MA: MIT Press, 2011. Print.

Frezzini, Francisca Ramirez, Ravindra Sachan, and Maryam Azimi. "Chapter 1: Review of Systems Engineering Scope and Processes." *Systems Engineering Tools and Methods.* Eds. Ali K. Kamrani, Maryam Azimi. Boca Raton, FL: Taylor & Francis Group, LLC, 2011. Web. 03 Nov 2017.

INCOSE. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities.* 4th ed. Eds. David D. Walden, Garry J. Roedler, Kevin J. Forsberg, R. Douglass Hamelin, Thomas M. Shortell. San Diego, CA: John Wiley & Sons, Inc, 2015. Web. 19 Sep 2017.

Kelly, Thomas. *Moon Lander: How We Developed the Apollo Lunar Module.* Washington, D.C.: Smithsonian Institution Press, 2001. Print.

Kossikoff, Alexander, William N. Sweet, Samuel J. Seymour, Steven M. Biemer. *Systems Engineering Principles and Practice.* 2nd ed. Hoboken, NJ: John Wiley & Sons, Inc., 2011. Web. 19 Sep 2017.

Johnson, Stephen B. *The Secret of Apollo: Systems Management in American and European Space Programs.* Baltimore: John Hopkins University Press, 2002. Print.

Lloyd, Dr. Nicholas. ISE 324 – Work Design. Department of Industrial & Systems Engineering and Engineering Management, University of Alabama at Huntsville, Fall 2017. Lectures and PowerPoint presentations.

Mesmer, Dr. Bryan. ISE 340 – Operations Research. Department of Industrial & Systems Engineering and Engineering Management, The University of Alabama in Huntsville, Fall 2017. Lectures.

NASA. *NASA Systems Engineering Handbook.* Rev 2. Washington D.C.: National Aeronautics and Space Administration, 2016. United States Government Publishing Office. NASA Technical Reports Server. PDF. 31 October 2017. https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf

Pellegrino, Charles R. and Joshua Stoff. *Chariots for Apollo: The Making of the Lunar Module.* New York: Atheneum Publishers, 1985. Print.

Petnga, Dr. Leonard. ISE 439/539 – Systems Engineering Modeling. Department of Industrial & Systems Engineering and Engineering Management, The University of Alabama in Huntsville, Fall 2018. Lectures and PowerPoint presentations.

Reichl, Eugen. *Project Apollo: The Early Years, 1960-1967.* Trans by David Johnston. Atglen, PA: Schiffer Publishing Ltd, 2016. Print.

Thomas, Dr. L. Dale. ISE 327 – Management Systems Analysis. Department of Industrial & Systems Engineering and Engineering Management, The University of Alabama in Huntsville, Spring 2017. Lectures and PowerPoint presentations.

---. ISE 627 – Engineering Systems. Department of Industrial & Systems Engineering and Engineering Management, The University of Alabama in Huntsville, Fall 2018. Lectures and PowerPoint presentations.

Wasson, Charles S. "Leading Complex System Development Projects in an Era of Outdated SE 'Groupthink' Paradigms." Given at The University of Alabama in Huntsville, 5 Nov 2018. PDF.

---. *Systems Engineering Analysis, Design, and Development.* 2nd ed. Hoboken, New Jersey: John Wiley & Sons, Inc., 2016.

University of Alabama in Huntsville, The. "Current Class Schedules." *UAH.* UAH, 2019. Web. 01 Jan 2019. https://www.uah.edu/cgi-bin/schedule.pl?

---. "Engineering Departments ISEEM Faculty & Staff." *UAH.* UAH, 2019. Web. 01 Jan 2019. https://www.uah.edu/eng/departments/iseem/faculty-staff

---. "Undergrad Course Descriptions ISE." *Catalog.UAH.* UAH, 2019. Web. 25 Jan 2019. https://catalog.uah.edu/undergrad/course-descriptions/ise/

Utley, Dawn. ISE 224 – Introduction to Industrial & Systems Engineering. Department of Industrial & Systems Engineering and Engineering Management, The University of Alabama in Huntsville, Fall 2016. PowerPoint presentations.

Endnotes

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Title image: LM-5 (Apollo 11)
https://en.wikipedia.org/wiki/Apollo_Lunar_Module
The UAH logo is taken from the UAH website in accordance with the rules of usage.
https://www.uah.edu/omc/resources/brand

[1] Adapted from questionnaire answers for EH 301 project.
[2] Taken from questionnaire answers for EH 301 project.
[3] Photograph taken by the author.
[4] De Weck, *et al*, 2.
[5] Buede, "1.2 Overview of Engineering Systems"; Utley, "Lecture 1 Introduction to Industrial & Systems Engineering".
[6] INCOSE, "2.2.2 Scientific Terminology Related to System Concepts"; Thomas, ISE 327 "Class 1 Overview," "Class 2 Systems Thinking"; De Weck, *et al,* 34.
[7] Thomas, ISE 327 "Class 1 Overview," "Class 2 Systems Thinking"; De Weck, *et al*, 32.
[8] INCOSE, "2.2.1 General System Concepts"; INCOSE, "2.2.1 General System Concepts"; NASA, 3; Thomas, ISE 327 "Class 1 Overview," "Class 2 Systems Thinking"; De Weck, *et al*, 39.
[9] INCOSE, "2.2.2 Scientific Terminology Related to System Concepts".
[10] Frezzini *et al,* "1.1 Introduction".
[11] De Weck, *et al*, 32.
[12] Lloyd, "Class 10 – Six Sigma Quality".
[13] NASA, 3.
[14] INCOSE, "2.9.3 Considerations for Systems Engineers".
[15] Petnga, "Lecture 2 Overview of Core System Concepts".
[16] INCOSE, "2.2.1 General System Concepts," "2.9.3 Considerations for Systems Engineers".
[17] De Weck, *et al*, xiv, 16ff, 29, etc.
[18] Buede, "1.1 Introduction"; Frezzini *et al,* "1.1 Introduction"; Thomas, ISE 327 "Class 5 Stakeholder and Organizational Influences".
[19] Thomas, ISE 327 "Class 4 The Project Life Cycle."
[20] Generated by the author.
[21] INCOSE, "2.6 Definition of Systems Engineering"; NASA, 3, 7.
[22] Wasson, 9.
[23] This subsection is based on Chapters 1 and 2 in De Weck, *et al.*

[24] Johnson, 3; Wasson, 13.
[25] Johnson, 209.
[26] Kossiakoff, et al, "1.2 Origins of Systems Engineering".
[27] Wasson, "Leading Complex System Development Projects in an Era of Outdated SE 'Groupthink' Paradigms".
[28] Generated by author with information from De Weck, *et al.*
[29] Kelly, 29.
[30] Compiled from Allday, xii; Reichl, 4-7, 16, 28, 44-45, 58, 129; Kelly, 16, 118, 124, 132, 151, 153, 188, 199, 205; Pellegrino & Stoff, 9-10.
[31] Johnson, 209-210; Thomas, ISE 627 "Class 3 The Systems Life Cycle".
[32] Kelly, 42.
[33] Kelly, throughout but especially 114-125, 149-154.
[34] Cutaway of the Lunar Module https://en.wikipedia.org/wiki/Apollo_Lunar_Module#/media/File:LM_illustration_02.jpg
[35] The components of Systems Thinking are taken from Thomas, ISE 327 "Class 2 Systems Thinking".
[36] Thomas, ISE 627 "Class 2 Systems Thinking".
[37] Wasson, 15; Thomas, ISE 627 "Class 2 Systems Thinking".
[38] INCOSE, "2.6 Definition of Systems Engineering"; Lloyd, all lectures.
[39] INCOSE, "2.9.2.3 Discovering Patterns".
[40] INCOSE, "2.9.2.3 Discovering Patterns".
[41] Thomas, ISE 627, "Class 2 Systems Thinking," 2018.
[42] De Weck, *et al*, 47-49; Thomas, ISE 327 "Class 3 Leadership & Teamwork".
[43] INCOSE, "2.9.2.4 Habits of a Systems Thinker".
[44] INCOSE, "2.9.2.4 Habits of a Systems Thinker".
[45] Thomas, ISE 627 "Class 2 Systems Thinking".
[46] Thomas, ISE 327 "Class 7 Technical Performance Measurement".
[47] INCOSE, "2.6 Definition of Systems Engineering," "2.8 Use and Value of Systems Engineering"; Thomas, ISE 327 "Class 4 The Project Life Cycle," "Class 6 Planning".
[48] INCOSE, "2.9.2.3 Discovering Patterns," "2.9.2.4 Habits of a Systems Thinker"; Lloyd, all lectures; Thomas, ISE 627 "Class 2 Systems Thinking".
[49] Wasson, 14.
[50] Wasson, 14.
[51] INCOSE, "2.9.2.4 Habits of a Systems Thinker".
[52] The following subsection titles are adaptations/combinations of the elements of systems thinking from Thomas, ISE 627 "Class 2

Systems Thinking," 2018. The definitions of each of the elements of systems thinking are from the same lecture by Thomas.
[53] Johnson, 118-119, 126.
[54] Kelly, 55, 79.
[55] Pellegrino & Stoff, 20.
[56] Reichl, 22.
[57] Reichl, 25; Kelly, 21; Pellegrino & Stoff, 21.
[58] Quoted or paraphrased in Reichl, 24-25.
[59] LOR sketch https://en.wikipedia.org/wiki/Lunar_orbit_rendezvous#/media/File:Lunar-orbit_rendezvous.jpg
[60] Reichl, 45-46.
[61] Kelly, 1-2.
[62] Pellegrino & Stoff, 22.
[63] Quoted/paraphrased in Pellegrino & Stoff, 22 – 23.
[64] Kelly, 216.
[65] Pellegrino & Stoff, 22.
[66] Reichl, 46.
[67] Kelly, 22-23; Pellegrino & Stoff, 25.
[68] Reichl, 22.
[69] Compiled from Kelly, 21, 216; Pellegrino & Stoff, 20-25; Reichl, 13, 20, 22-25, 28.
[70] Direct vs. LOR lander size comparison https://en.wikipedia.org/wiki/Lunar_orbit_rendezvous#/media/File:Comparison_of_Lander_Sizes_-_Direct_vs_LOR.gif; from Pellegrino & Stoff originally.
[71] Pellegrino & Stoff, 24; Reichl, 27.
[72] Kelly, 2, 22, 25.
[73] Reichl, 28.
[74] Reichl, 44-45.
[75] Kelly, 2.
[76] All of the main concepts in this section come from Thomas, ISE 327.
[77] Buede, "1.2 Overview of the Engineering of Systems".
[78] Frezzini *et al,* "1.2 The Need for Systems Engineering".
[79] NASA, 6.
[80] NASA, 3-5; Thomas, ISE 327 "Class 3 Leadership & Teamwork".
[81] Thomas, ISE 327 "Class 3 Leadership and Teamwork".
[82] INCOSE, 2.10 Systems Engineering Leadership"; Thomas, ISE 327 "Class 3 Leadership and Teamwork".
[83] INCOSE, "2.11.1 SE Professional Ethics"; Thomas, ISE 327 "Class 21 Engineering Ethics".
[84] Thomas, ISE 327 "Class 3 Leadership & Teamwork".

[85] Johnson, xi.
[86] NASA, 13.
[87] NASA, 13; Thomas, ISE 327 “Class 4 The Project Life Cycle”.
[88] Thomas, ISE 327 “Class 4 The Project Life Cycle”.
[89] Thomas, ISE 327 “Class 6 Planning”.
[90] List compiled from INCOSE, NASA, and Thomas, ISE 327.
[91] Petnga, “Lecture 4 System Modeling Foundations”.
[92] De Weck, *et al,* 36.
[93] Buede, “1.1 Introduction”; Thomas, ISE 327 “Class 4 The Project Life Cycle”.
[94] Lloyd, all lectures, Thomas, ISE 327 “Class 5 Stakeholders & Organizational Influences”.
[95] INCOSE, “2.6 Definition of Systems Engineering”; NASA, 16.
[96] NASA, 63.
[97] Thomas, ISE 327 “Class 5 Stakeholders and Organizational Influences”.
[98] NASA, 16.
[99] INCOSE, “4.3.1.4 Process Activities”.
[100] Buede, “Preface”.
[101] INCOSE, “4.3.2.2 Characteristics and Attributes of Good Requirements”; Mesmer, Lecture 9.
[102] INCOSE, “4.3.2.2 Characteristics and Attributes of Good Requirements”; Thomas, ISE 327 “Class 7 Technical Performance Measurement”.
[103] INCOSE, “5.7.2 Elaboration”; Thomas, ISE 327 “Class 7 Technical Performance Measurement”.
[104] Thomas, ISE 327 “Class 7 Technical Performance Measurement”.
[105] Thomas, ISE 327 “Class 5 Stakeholders and Organizational Influences”; De Weck, *et al*, 16.
[106] De Weck, *et al*, 46-47.
[107] Lloyd, “Six Sigma Quality”.
[108] NASA, 9, 16; Thomas, ISE 327 “Class 6 Planning”.
[109] Buede, “Preface”.
[110] NASA, 26-32.
[111] NASA, 9.
[112] Thomas, ISE 627 “Class 18 Systems Integration”.
[113] NASA, 15.
[114] NASA, 107ff.
[115] INCOSE, “4.10 Transition Process”.
[116] NASA, 9-11.
[117] INCOSE, “2.8 Use and Value of Systems Engineering”
[118] NASA, 10; Thomas, ISE 327 “Class 4 The Project Life Cycle.”
[119] Generated by the author.

[120] Kelly, 23-25, 74-76.
[121] Kelly, 43.
[122] Kelly, 74, 76.
[123] Reichl, 58.
[124] Kelly, 74-76.
[125] Kelly, 75. Note that Reichl indicates 220 lbs of equipment and 66 lbs of lunar material (58).
[126] Reichl. 58-59.
[127] Kelly, 76-77.
[128] Reichl, 46, 144.
[129] Kelly, 28-29.
[130] Johnson, 141-142.
[131] Pellegrino & Stoff, 25, Reichl, 46.
[132] Reichl, 47, Thomas, ISE 627 "Class 22 Risk Assessment".
[133] Reichl, 63.
[134] Reichl, 74.
[135] Kelly, 81.
[136] Kelly, 76.
[137] Kelly, 121-122.
[138] Apollo launch configuration https://history.nasa.gov/diagrams/ad003.gif
[139] Kossiakoff, et al, "1.4 Systems Engineering as a Profession".
[140] NASA, 3.
[141] De Weck, *et al*, 29.
[142] Kossiakoff, et al, "1.4 Systems Engineering as a Profession," "1.5 Systems Engineer Career Development Model," "1.7 Summary".
[143] Buede, "1.1 Introduction"; Kossiakoff, et al, "1.1 Objectives".
[144] NASA, 4.
[145] INCOSE, "2.8 Use and Value of Systems Engineering"; Thomas, ISE 327 "Class 20 Risk Management".
[146] De Weck, *et al,* 30.
[147] De Weck, *et al*, 26, etc.; Thomas, ISE 327 "Class 3 Leadership & Teamwork".
[148] INCOSE, "2.11 Systems Engineering Professional Development"; Kossiakoff, et al, "1.5 Systems Engineer Career Development Model".
[149] Kossiakoff, et al, "1.5 Systems Engineer Career Development Model".
[150] Kossiakoff, et al, "1.4 Systems Engineering as a Profession".
[151] Kossiakoff, "1.4 Systems Engineering as a Profession," "1.5 Systems Engineer Career Development Model".
[152] Generated by the author.
[153] Allday, xii.

[154] Petnga, “ISE 439/539: Review Midterm Exam and Project.”
[155] Kelly, 263.
[156] Tom Kelly during Apollo 11 mission https://en.wikipedia.org/wiki/Thomas_J._Kelly_(aerospace_engineer)#/media/File:MaynardKellySPAN.JPG
[157] Compiled from Kelly, 1, 2, 6, 10, 11, 13-15, 19-25, 28-29, 35-36, 38-39, 46; Johnson, 118; Pellegrino & Stoff, 9-10.
[158] Generated by the author with personal knowledge and information from the UAH website.
[159] Generated by the author with personal knowledge and information from the UAH website.
[160] All definitions are written by the author with information compiled from multiple sources, listed in the Works Cited.