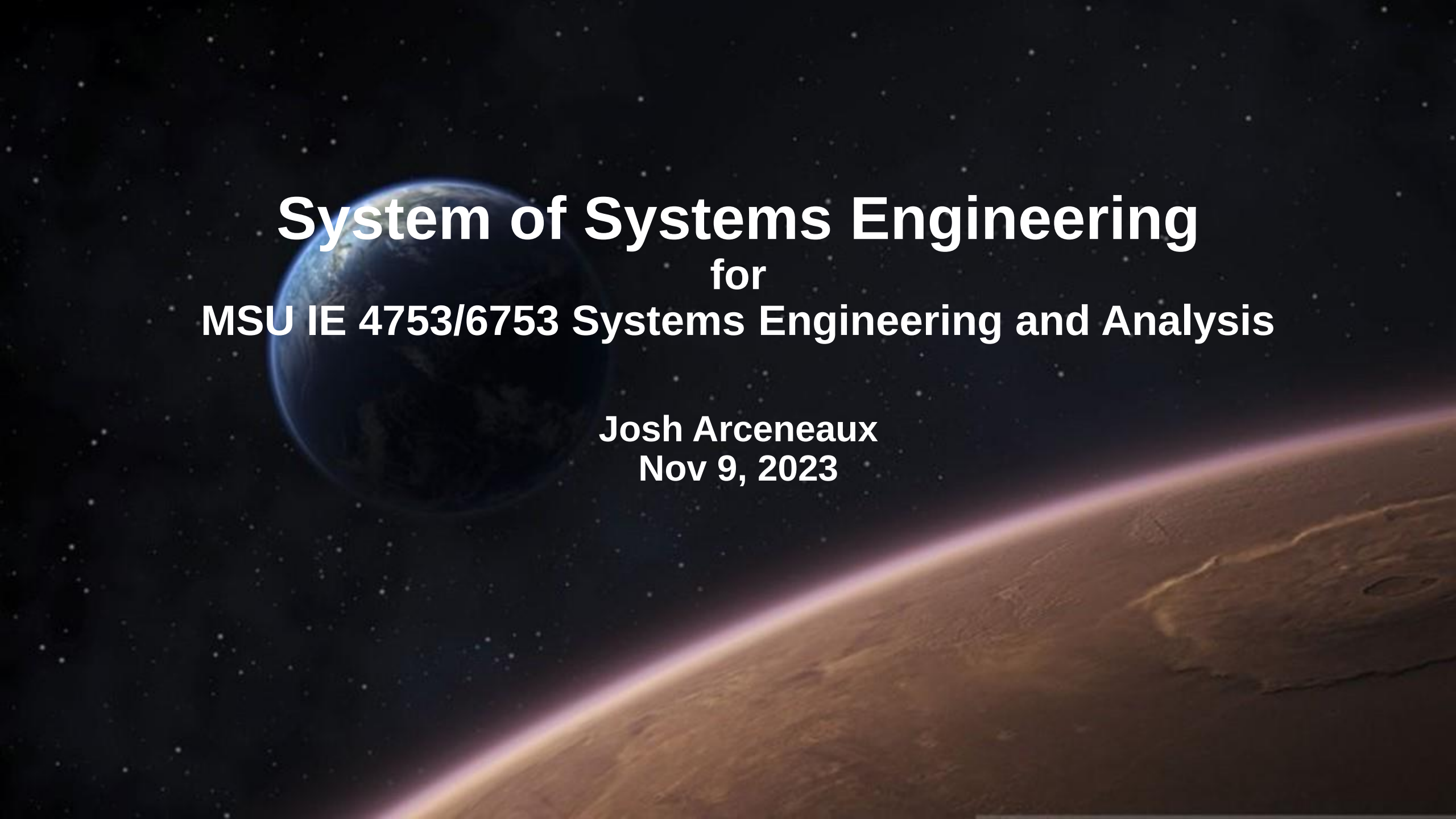

System of Systems Engineering

for

MSU IE 4753/6753 Systems Engineering and Analysis

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The views and opinions expressed in this presentation and seminar are those of the author and do not necessarily reflect the official policy, opinion, or position of their employer.

Agenda

- A brief history of SE&I in spaceflight and exploration
- System of Systems Engineering
- Influences on Systems Engineering Execution
- Anchor Points
- Moon-to-Mars Example
- Perspectives on the SE&I Profession and Your Career

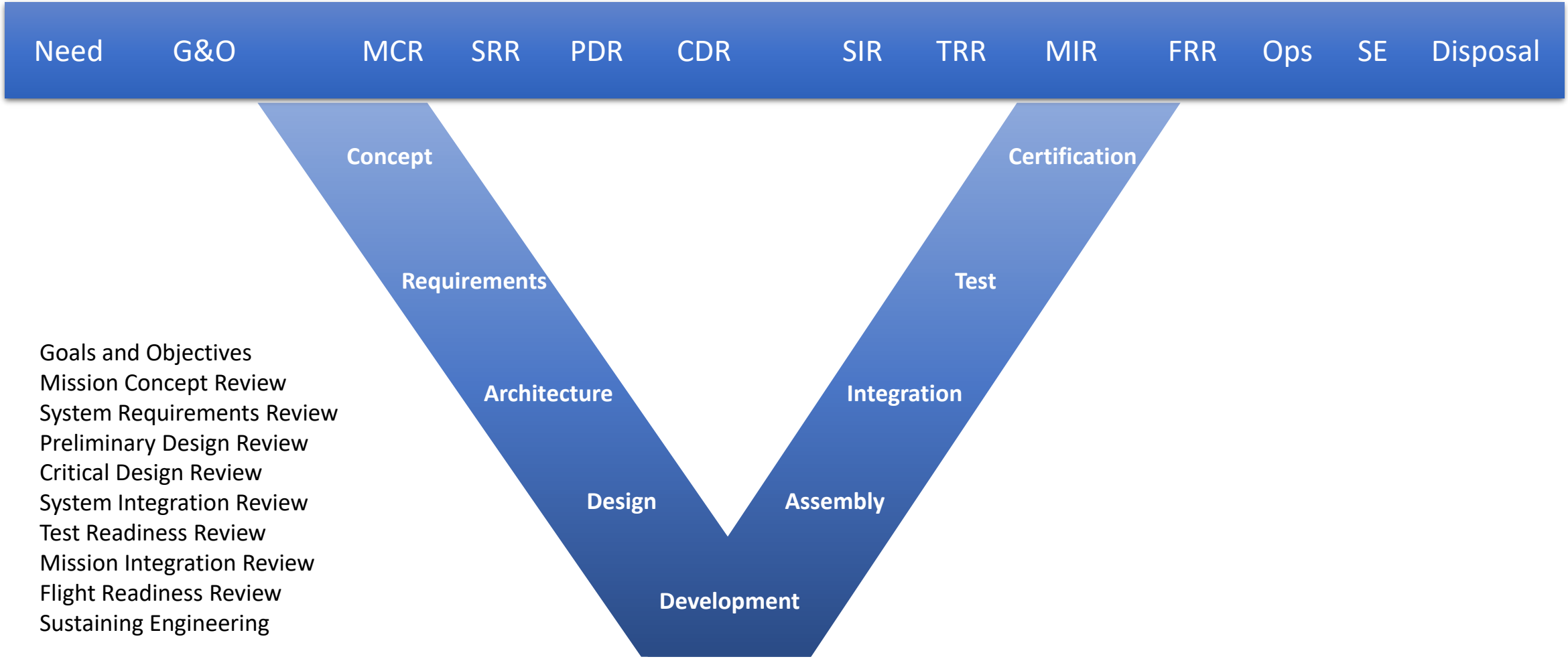
Rough timeline of SE&I in space exploration

1903	First powered flight.
1920’s – 1930’s	Golden age of flight - What is SE&I?
1940	First recorded instance of Systems Engineering as a practice in Bell Labs to deal with more complex systems.
1940’s – 1980’s	Hot and Cold war arms race, Space Race (Mercury, Gemini, Apollo), Space Shuttle, Information Age begins, and system engineering evolves as systems become more complex. Technology begins to change SE&I through modeling complex systems.
1990	NCOSE is started for systems engineering professionals to collaborate and advance the profession.
1990’s – 2010’s	ISS and more complex DoD systems start to need System of Systems Engineering to handle highly dependent and interactive ecosystems with many interfacing systems.
2020’s+	Golden age of space exploration with Artemis and commercial space flight companies building a budding space economy.

We are at the end of the beginning!

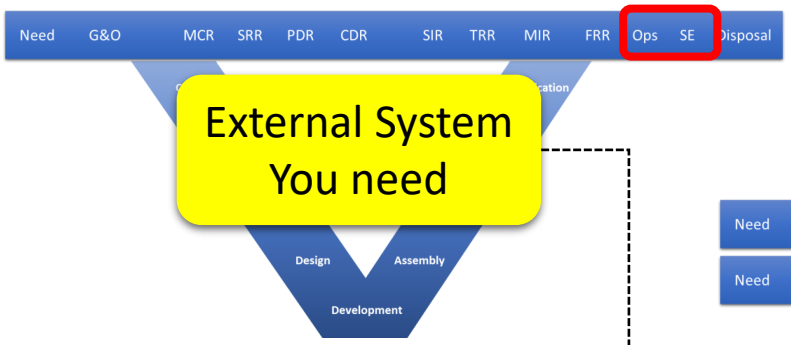
- Space exploration has entered a period of rapid transformation.
- Once the domain of two nations and almost exclusively a government endeavor, the past few years has seen a significant increase in global participation by a multitude of nations, commercial companies, and wealthy individuals.
- Not only have we seen and increase in participants, but the number of vehicles also continues to increase while also increasing in complexity and becoming more dependent on each other.
- This in turn drives more complex systems-of-systems architectures that the profession of SE&I will need work with.

Everyone is familiar with this, and its many variations?



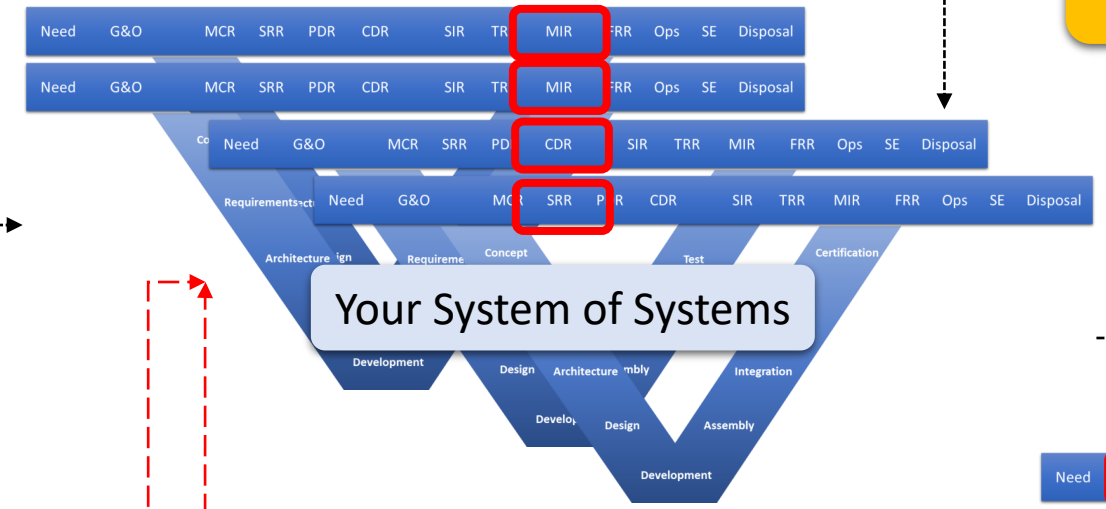
G&O: Goals and Objectives
MCR: Mission Concept Review
SRR: System Requirements Review
PDR: Preliminary Design Review
CDR: Critical Design Review
SIR: System Integration Review
TRR: Test Readiness Review
MIR: Mission Integration Review
FRR: Flight Readiness Review
SE: Sustaining Engineering

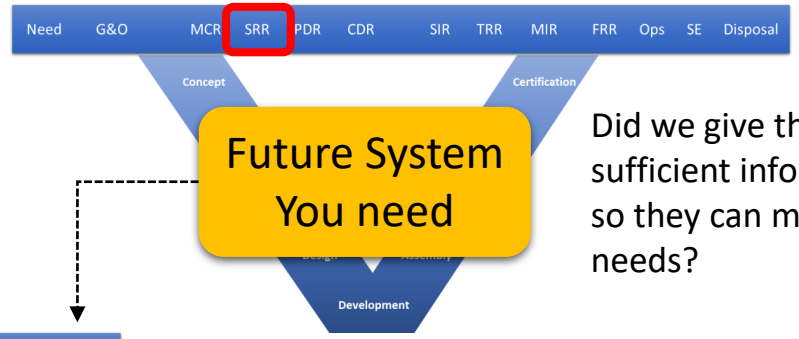
In many cases, it's more like this



You're stuck with with what they have, how can you make this work?

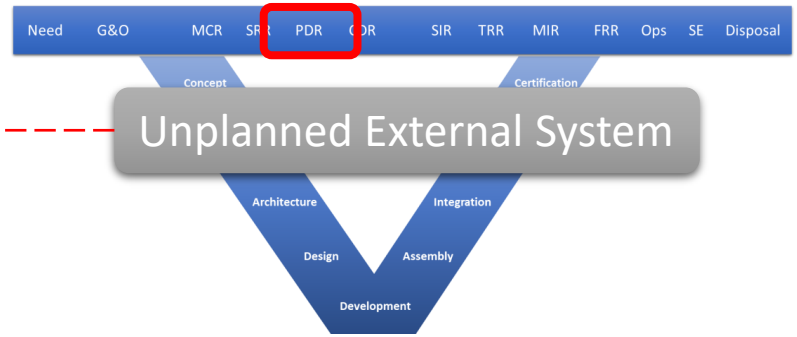
How does this all work together?



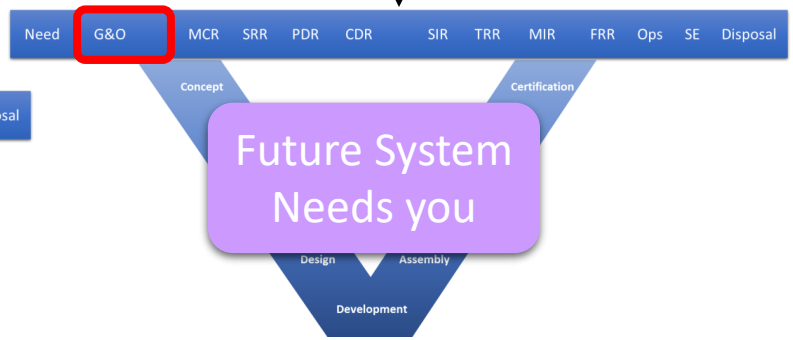


Did we give them sufficient information so they can meet my needs?

What's the impact to me and what can I do about it?



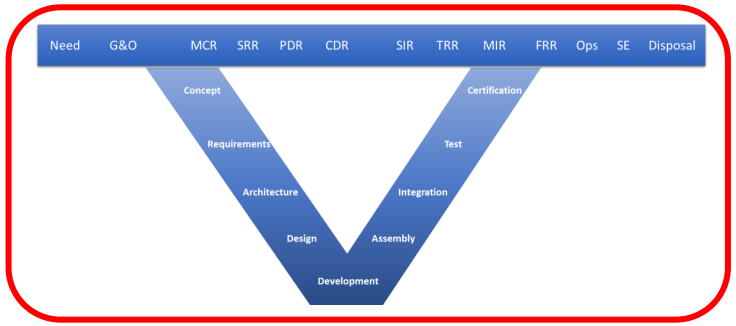
How does this help me, and can I influence it?



How much will this impact you and what can you give?

Different acquisition models, added complexity for SE&I

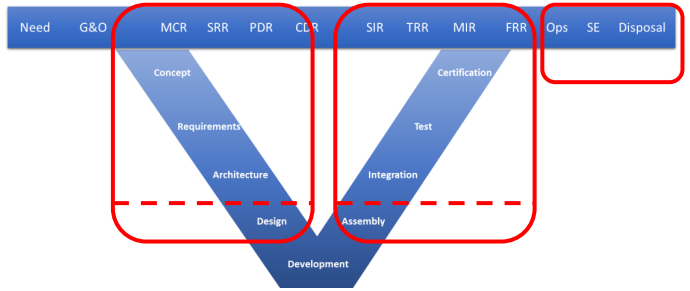
Developer-Owner-Operator model



- Oversight
- You own everything
- Mission, systems, integration
- You own the system data
- Often CPFF/AF or T&M Contracts for support

- Requires all types of SE&I professionals as you are defining the mission, designing and building the systems, and are the performer for all things T&V, certification, and operations.
- Flexibility is greatest but so is the potential for scope creep putting pressure on the SEI team to constantly assess and manage mission and system scope.

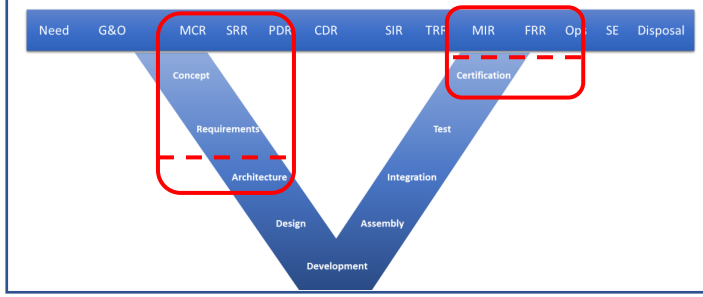
Buyer-Owner-Operator model



- Oversight
- You take ownership of everything
- Mission, systems, integration
- You own the system data you put in the contract
- Often CPFF or T&M Contracts for support and system development

- SE&I focus on full lifecycle management of the systems and typically has significant involvement and oversight of the design.
- SE&I must capture sufficient engineering information to take ownership of, operate, and sustain the system.

Buyer of Services

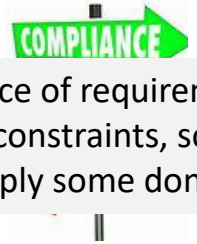


- Insight
- You own the mission
- Service providers own the systems
- Integration is…interesting
- You own very little system data
- Often FFP contracts for end-to-end services

- SE&I focuses on early lifecycle concept and requirements and mission definition putting a premium on defining what the systems will need to do, not necessarily how.
- Flexibility constrained by the services you procure.

Now mix in programmatic, business, and other considerations

International partners and agreements drive what you can/cannot do



A source of requirements and constraints, some apply some don't

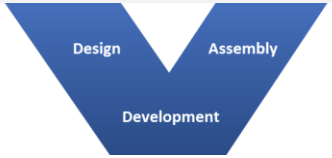
What comes out of SE&I needs to align collaboratively with industry capabilities and business models

SCOPE

You will concurrently receive these and decompose them for the next level down

Decisions and information outside of SE&I have an impact and what occurs within SE&I

What SE&I produces impacts them as well



SE&I is fundamentally a people-to-people profession

Ultimately the SE&I function, and professionals, need to reduce risk and drive value consistent with what the stakeholders value, or we are just overhead.

Technology is an enabler, not the systems engineer

In complex systems and systems of systems, anchor points can help

- Anchor Points can come in many forms, some more concrete or abstract than others.
- A “core” technical baseline provides one anchor point.
  - Concept of Operations
  - Requirements
  - Architecture (functional and physical)
  - Configurations
  - Interfaces
  - Verification and Validation
  - Design Certification
- This forms the anchor to integrate
  - Your scope as decomposed from above.
  - The scope you decompose and parse out to the level below.
  - The engineering lifecycle information generated to bring a system of systems to life.

- Later in the lifecycle a performance (integrated and system) and mission specific baselines will become an anchor - this is an evolution of the technical baseline from DDT&E to Planning and Operations.
  - Mission Plan, Timeline, Activities
  - Mission performance parameters
  - System manifested for the mission
  - When these systems together and how we do that
  - What these systems will interface for and when
  - Determination of mission closure
  - Flight certification
- Defines how you will use the systems in an actual mission and if they fit within the performance margins of the design certification.
  - May need waivers or alternate mission plans if it doesn’t
  - This alternate mission analysis represents a core SE&I function throughout the lifecycle
- As more flight experience and data becomes available, the performance baseline will evolve.

Application to Moon-to-Mars Ecosystem

A **Earth Ops**: Supply Chain and Logistics to ensure all systems can meet launch schedules across a campaign and mission and to receive and process returning systems at mission end. Includes all capability to plan, train, and fly.

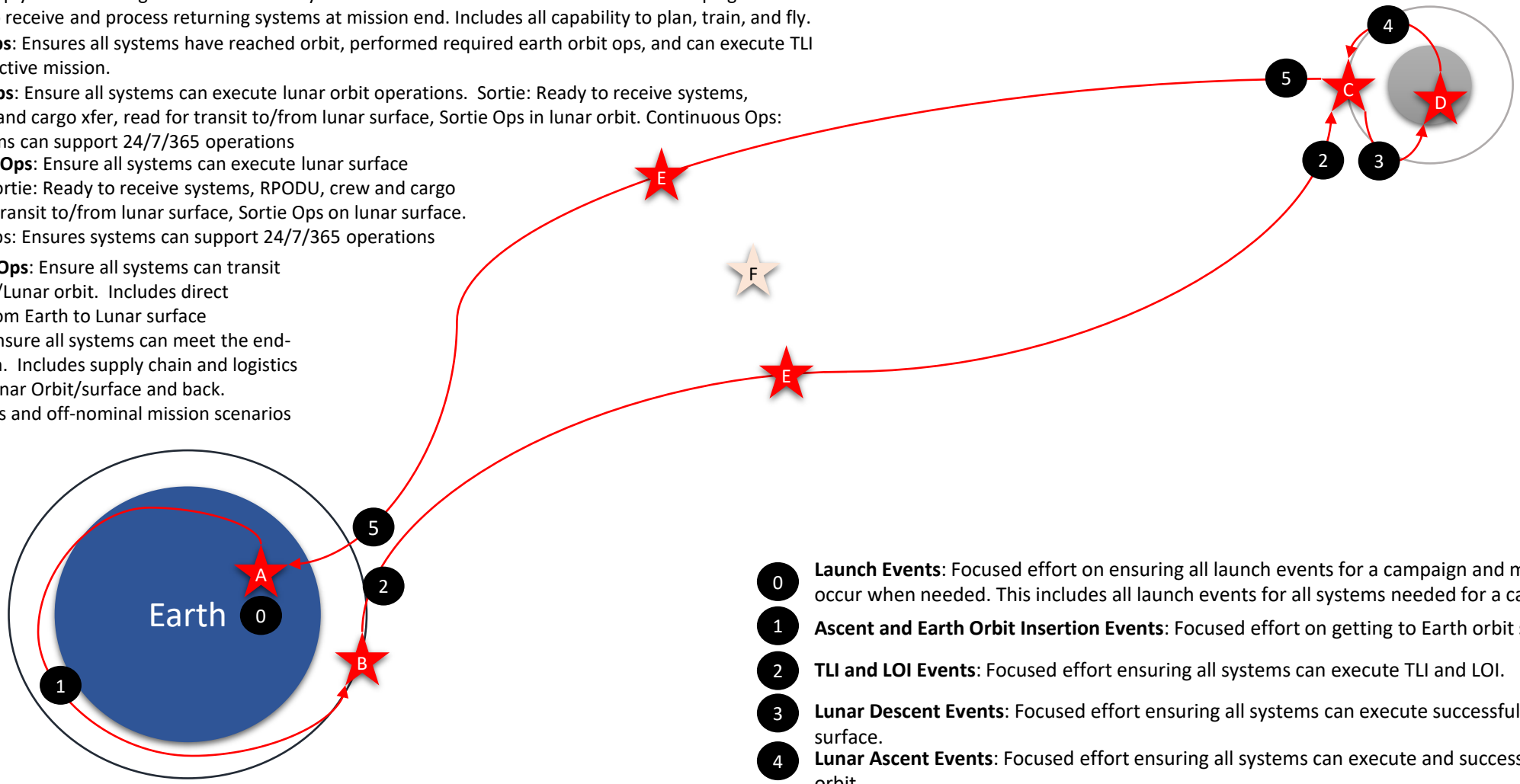
B **Earth Orbit Ops**: Ensures all systems have reached orbit, performed required earth orbit ops, and can execute TLI for their respective mission.

C **Lunar Orbit Ops**: Ensure all systems can execute lunar orbit operations. Sortie: Ready to receive systems, RPODU, crew and cargo xfer, read for transit to/from lunar surface, Sortie Ops in lunar orbit. Continuous Ops: Ensures systems can support 24/7/365 operations

D **Lunar Surface Ops**: Ensure all systems can execute lunar surface operations. Sortie: Ready to receive systems, RPODU, crew and cargo xfer, read for transit to/from lunar surface, Sortie Ops on lunar surface. Continuous Ops: Ensures systems can support 24/7/365 operations

E **Lunar Transit Ops**: Ensure all systems can transit to/from Earth/Lunar orbit. Includes direct trajectories from Earth to Lunar surface

F **End-to-End**: Ensure all systems can meet the end-to-end mission. Includes supply chain and logistics for Earth to Lunar Orbit/surface and back. Includes aborts and off-nominal mission scenarios



0 **Launch Events**: Focused effort on ensuring all launch events for a campaign and mission can successfully occur when needed. This includes all launch events for all systems needed for a campaign and missions.

1 **Ascent and Earth Orbit Insertion Events**: Focused effort on getting to Earth orbit successfully

2 **TLI and LOI Events**: Focused effort ensuring all systems can execute TLI and LOI.

3 **Lunar Descent Events**: Focused effort ensuring all systems can execute successfully and reach the lunar surface.

4 **Lunar Ascent Events**: Focused effort ensuring all systems can execute and successfully reach the lunar orbit

5 **TEI and Return Events**: Focused effort ensuring all system can return to Earth from lunar orbit/surface

It's only going to get more complex, more distributed, and more resource intensive

- With the mass proliferation of space economy companies, SE&I (with emphasis on the "I") must evolve to meet government and industry where they are at and more importantly where they are heading.

- We are no longer building one-off specialized tightly coupled well integrated systems for a specific mission; we are building a sustainable ecosystem with a mixture of tightly and loosely coupled systems that can perform a multitude of missions.

- The SE&I toolbox must and is evolving rapidly with model-based systems engineering gaining tracing, advances in digital engineering, and new possibilities with AI/ML and analytics not possible just a few years ago.

- Silicon Valley is colliding with Space Exploration and SE&I professionals, practices, and tools must keep up.

Your Future as an SE&I professional

- The world and the heavens are yours to explore.
- The world at large continues to shift towards a “systems thinking” approach for complex problems – this bodes well for systems engineers.
- Scary tidbit: In the aerospace industry alone, nearly 50% of the workforce can or will retire within the next five to seven years.
- Corollary: It takes roughly five-years for a new graduate to become proficient as a systems engineer, and that is only in one or two aspects of SE&I.
- Technology (Digital Engineering, Model Based Systems Engineering, AI/ML, etc.) can accelerate this to a degree and has quickly become “table stakes” but cannot replace failure as a teacher.

Questions and Answers