Jet Propulsion Laboratory
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Overview of Planetary Mission Formulation

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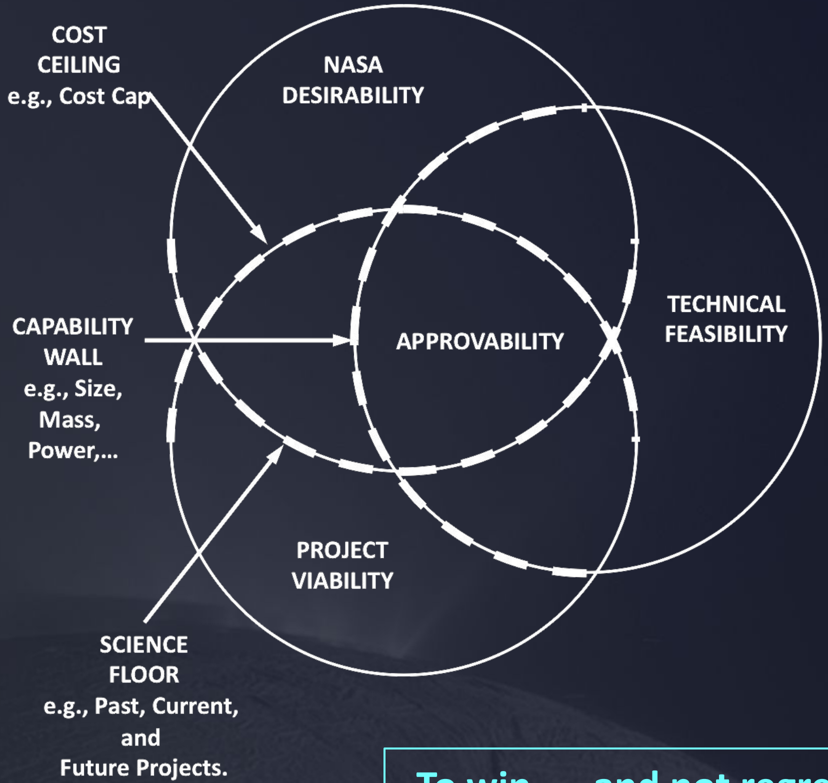
What is formulation?

The goal of early mission formulation?

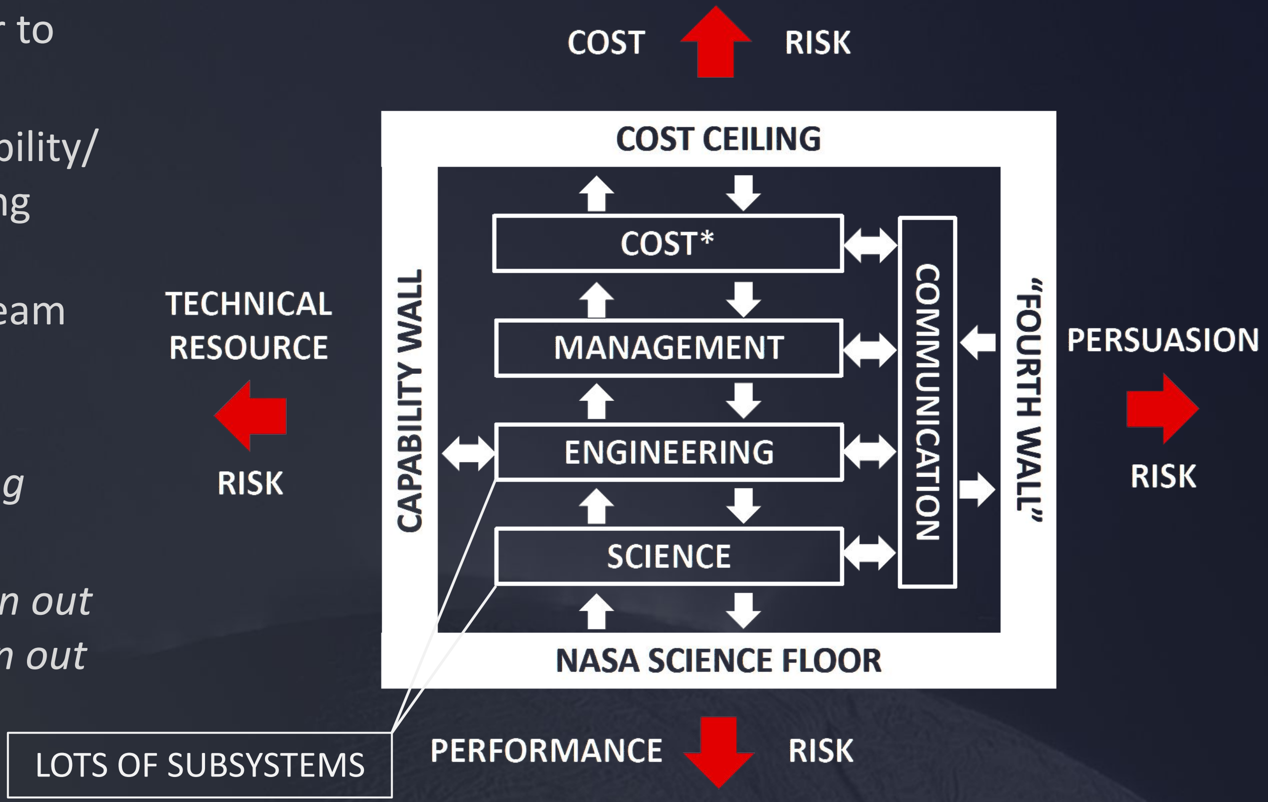
- NASA SP-2016-6105 Rev2 “NASA Systems Engineering Handbook”: *The purpose of Pre-Phase A Concept Studies is to produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope.*



To win … and not regret it.

Optimise a design to maximize approvability/selectability/desirability

- **Conduct trades** in order to optimize a design.
- **Maximization** of desirability/ approvability (compelling science return) whilst minimizing risk to the team and sponsor.
- **Trade:** *"To exchange something for something else, an alternative."*
- N.B. *"You will always run out of money before you run out of science"* – A. Nash



Science Traceability:
Getting Started

What is a Science Traceability Matrix?

"A good science traceability matrix (STM) contains all the high-level information needed to understand why a given proposal is relevant, what it purports to accomplish for science, how it intends to accomplish it, and what expected products and knowledge will result from it's success."
– Weiss *et al*. (2005).

Requirement B-17. Traceability from science goals to measurement requirements to instrument requirements (functional and performance), and to top-level mission requirements shall be provided in tabular form and supported by narrative discussion. Projected instrument performance shall be compared to instrument performance requirements.

- Common framework, tool for storytelling, negotiating requirements, communication of mission definition and completeness tracking. *Does not necessarily state if the mission is capable of those measurements (see MTMs).*
- Reality: Science Traceability Matrices are often generated retroactively in order to justify requirements, not pro-actively to inform trades. As a result, they often are very limited in terms of both Science and Traceability. This is bad practice.

The Standard NASA STM Template

Form A — Form B

Science Goals	Science Objectives	Scientific Measurement Requirements: Physical parameters	Scientific Measurement Requirements: Observables	Instrument Requirements		Projected Performance	Mission Requirements (Top Level)
GOAL 1	Objective 1	Column Density of Absorber	Absorption Line	Alt. Range	XX km	ZZ km	Observing strategies: requires yaw & elevation maneuvers
		Density and Temperature of Emitter	Emission Line				Launch window: to meet nadir and limb overlap requirement. Window applies day-to-day.
		Size of Features	Morphological Feature	Vert. Resolution	XX km	ZZ km	Need NN seasons to trace evolution of phenomenon
				Horiz. Resolution	XX deg x XX lat x XX long	ZZ deg x ZZ lat x ZZ long	
			Rise Time of Eruptive Phenomena	Temperature Resolution	XX min	ZZ min.	Need MM months of observation to observe variability of phenomenon.
				Precision	XX K	ZZ K	
				Accuracy	XX K	ZZ K	

Not especially helpful examples

Sources:
Modified from Discovery 2019 AO,

Form A: Goals and Objectives

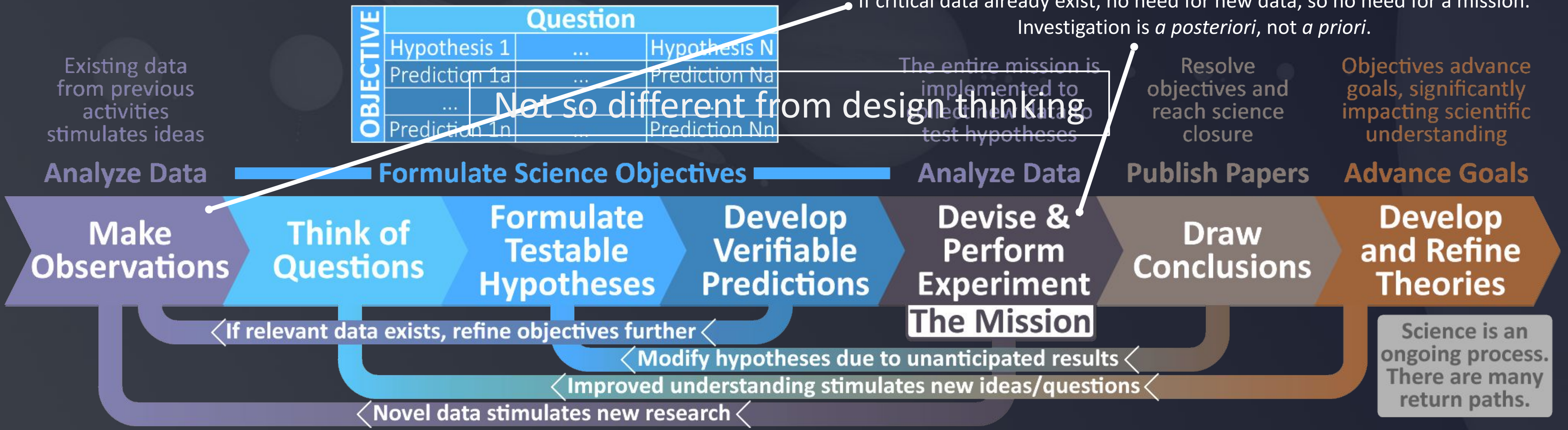
- *NASA Definition:* "**A goal is understood to have a broad scope** (e.g. discovery whether life exists elsewhere in the Universe; discovery how and why Earth's climate and environment are changing), **while an objective is understood as a more narrowly focused part of the strategy to achieve a goal** (e.g., identify specific chemical, mineralogical or morphological features on mars that provide evidence of past or present life there; understand and improve predictive capacity for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition). **Proposed investigations must achieve their proposed objectives; however, the investigation might only make progress towards a goal without fully achieving it.**" – Discovery 2019 AO

How to start: *a priori* scientific method

What makes a credible mission science objective?

Couched in terms of the Scientific Method, mission objectives encapsulate **questions**, **testable hypotheses** and **verifiable predictions**. It should have a clear path to **deductive science closure**, based on new data, leading to **fundamental conclusions** about cause and effect that advance science understanding. *To be implementable, hypotheses and predictions should ideally be defined as a data-driven mathematical model.*

If critical data already exist, no need for new data, so no need for a mission. Investigation is *a posteriori*, not *a priori*.



Example of a goal and an hypothesis-based objective

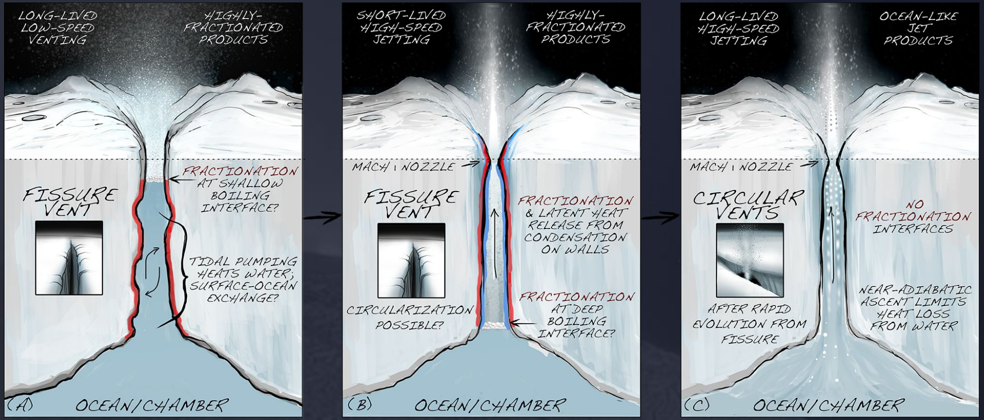
FEATURES:

- A clear link between goal and objective demonstrating logical flow and "traceability".
- Two clearly elucidated hypotheses, with (at this stage qualitative) predictions that inform what measurements are to be made.
- Explanatory paragraphs
- No numbers!

Science Goals (quotes from Decadal Survey)	Science Objectives
Understand a previously unexplored building block of planet formation: iron cores. What were the initial stages, conditions, and processes of solar system formation and the nature of the interstellar matter that was incorporated? (Vision and Voyages p70, first of three major questions on the formation and evolution of the solar system) What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play? (V&V p70, third of three major questions on the formation and evolution of the solar system) Understand how and when planetesimals were assembled to form planets. (V&V p94, Understanding the role of primitive bodies as building blocks for planets and life) Did asteroid differentiation involve near-complete melting to form magma oceans, or modest partial melting? (V&V p93, Nature and chronology of planetesimal differentiation)	**A. Determine whether Psyche is a core, or if it is primordial unmelted material.** Was it a molten core of a differentiated planetesimal: If Psyche's structure predominantly reflects solidification from a liquid it will have a radial density structure, while if it was significantly disrupted and/or was never molten it should have a heterogeneous density structure. Further, if it was once molten, its nickel, sulfur, and magnetic field characteristics may be able to determine whether it solidified from the inside out or the outside in. Did it instead accrete from primordial highly reduced metallic materials: If it never melted and differentiated but instead accreted as is, it will lack magnetic fields and large Ni variations, and its silicate fraction will be intimately mixed with the metal phase.

Example objective: Nature of Enceladus' plume

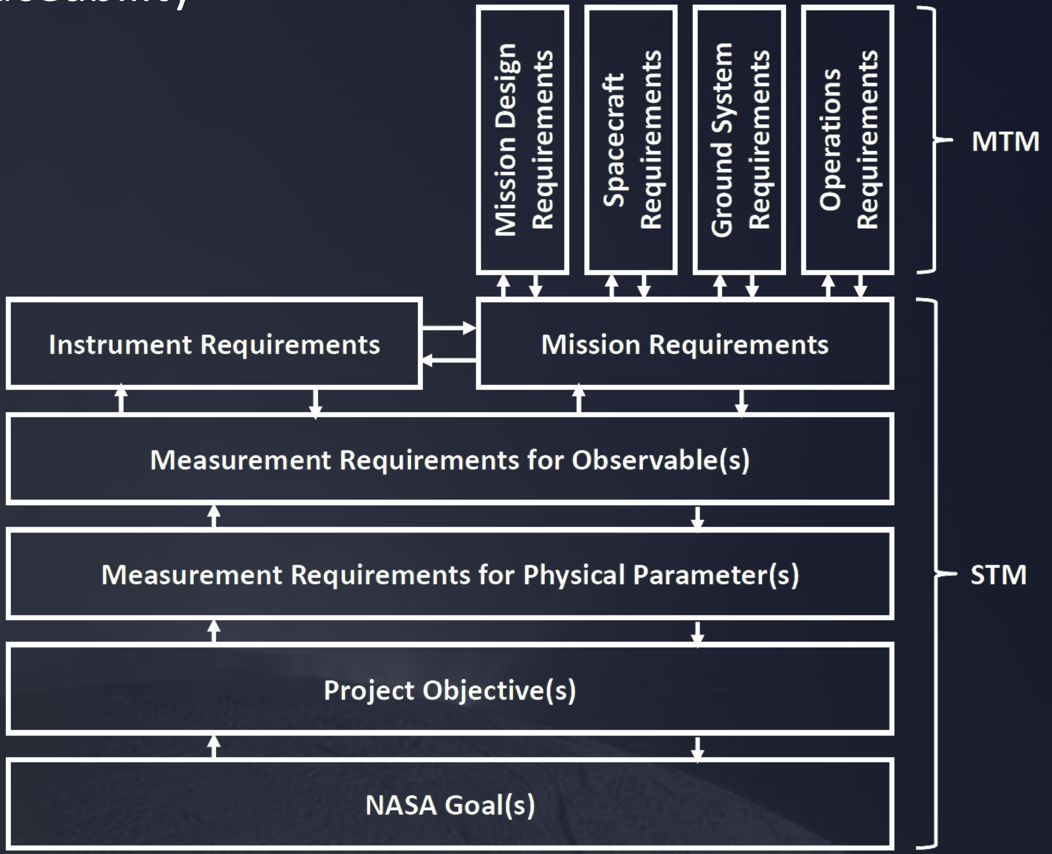
- Distinguish between different classes of eruption transport models for supplying Enceladus' jets and plume → How do the jets sample the ocean?
  - Nakajima & Ingersoll (2016)
    - I/V low, fissure or point sources, superthermal, co-plume not required
  - Kite & Rubin (2016)
    - I/V very low, fissure sources, thermal, co-plume not required
  - Mitchell, Rabinovitch et al. (2024)
    - I/V high, point sources, superthermal, co-plume required
- Each has consequences for observables, jet content, etc., and their differences enable resolution between eruption models



Science Traceability:
Flowdown to Engineering

Framework of science-to-mission traceability

- Measurements and science requirement flowdown
- **Every arrow pair represents a model** (conceptual, scientific or engineering)
  - Up arrows are requirements
  - Down arrows are performances
  - *Model maturity differs*
- In principle, **every model is coupled** and must be solved iteratively.
- Ideally this should be done within a rigorous **VVUQ framework**, but this is not always done.



Science Traceability: Parallels in Information/Data Science

STM Column	Science **Goals**	Science **Objectives**	**Measurement** Requirements **Physical Parameters**	**Observables**	**Instrument** Requirements	**Mission** Requirements
DIKW Hierarchy Levels	**Wisdom** *Applicable* Knowledge Know *Why*	**Knowledge** *Associated* Information Know *How*	**Information** *Categorized* Data Know *What*	**Data**		
Associated Data Product Levels	[None]	**Model-Based** Products EOSDIS Level 4 model output data products CODMAC Level 7 (correlative) data products	**Derived** Products PDS4 Derived data products EOSDIS Level 2 & 3 geophysical parameter data products CODMAC Level 5 (derived) data products	**Processed** Products PDS4 Calibrated data products EOSDIS Level 1 spectral, radiometric, and geometric data products CODMAC Level 2 (edited), 3 (calibrated), and 4 (resampled) data products	**Unprocessed** Products PDS4 telemetry & raw data products EOSDIS unprocessed Level 0 telemetry data products CODMAC Level 1 raw telemetry data products	
Examples	**Validated** causal models	**Tests** of models of planetary atmospheres, climate, astrophsical phenomena, etc.	**Maps** of surface temperature, atmospheric profiles, topography or composition	Calibrated **observations** of radiances, images, spectra, etc.	Instrument and Spacecraft **telemetry**	

A hierarchical framework for defining science goals & objectives

WISDOM: Advance understanding of the nature of the universe
Address "**Why...?**", by contributing to fundamental big-picture science
Form: broad rules/laws, with predictive power

KNOWLEDGE: Resolve between specific hypotheses
Address "**How...?**", for identifying causative processes
Form: science closure and conclusions

INFORMATION: Constrain the nature of an object
Address "**What...?**", by parameterizing the universe
Form: scientifically-meaningful maps, plots, etc.

DATA: Measure signals with instruments
Limited intrinsic scientific value
Form: raw/calibrated images, spectra, etc.

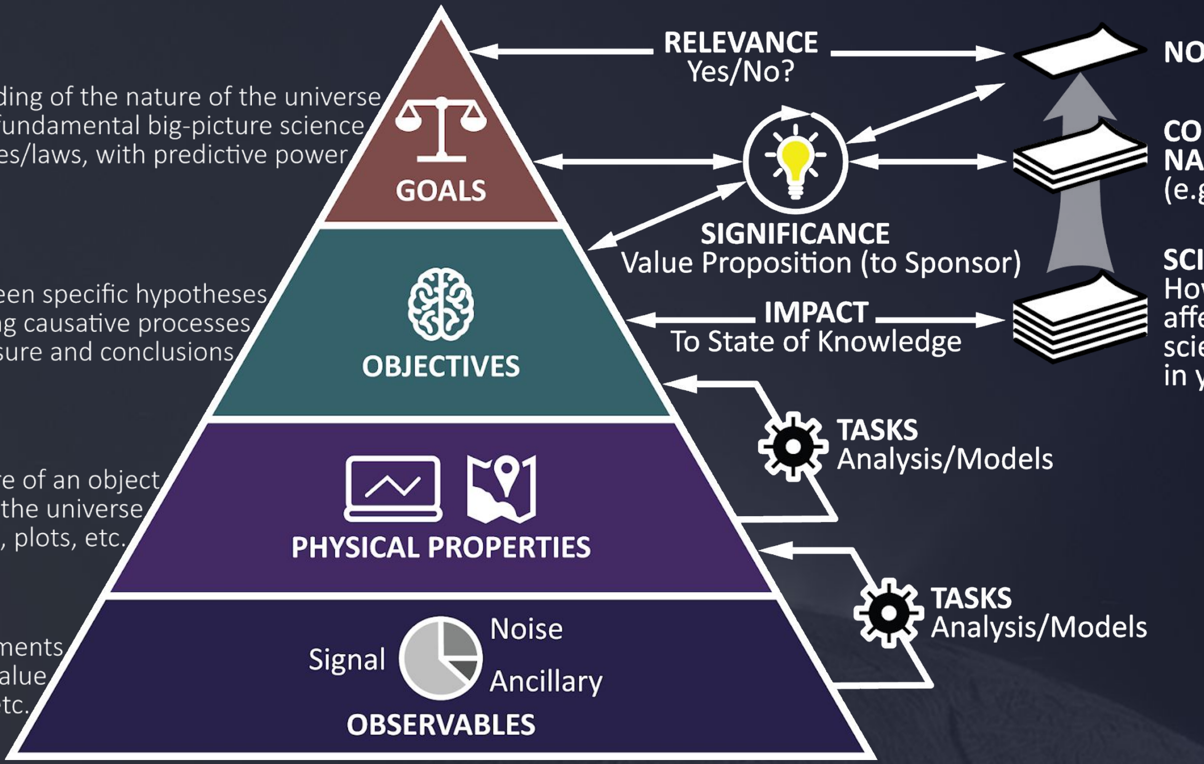


Figure: Based on the DIKW pyramid, an hierarchical structure used in information theory. The DIKW pyramid is of uncertain origin, but likely inspired by T.S. Eliot's poem "Choruses". This version by Karl Mitchell, JPL

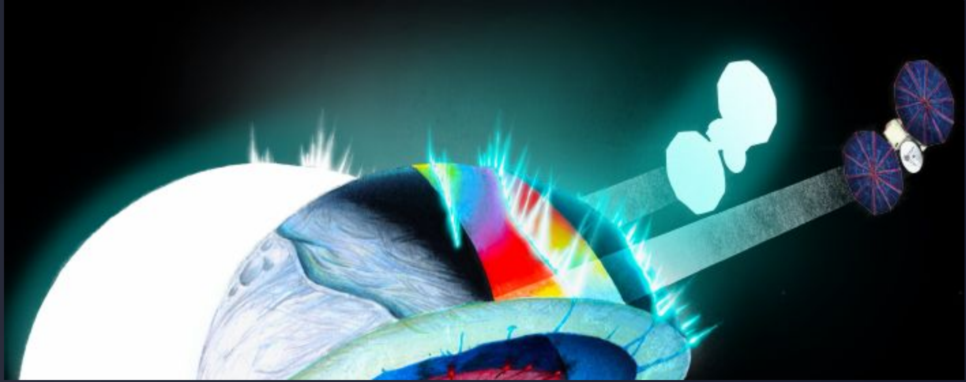
Production of stable requirements from science to engineering

- Begin at the beginning, and resist the urge to jump ahead.
- Starting in the middle usually results in convergence problems.
- This leads to unverifiable and unstable requirements.
- The result is excess cost (over-specified) or requirements creep (under-specified).
- However, often scientists will <u>induce</u> an observable requirement, especially if rushed.
- Scientists should be encouraged to take time formulating their objectives before deriving their requirements within a deductive hypothesis-prediction framework.

Production of stable requirements from science to engineering

- Flowdown starts with specification of physical parameter prediction verification thresholds: Level 1 requirements.
- Scientists and engineers must then collaborate to iterate towards an optimal design.
- The faster and more precisely the team can iterate, the more rapidly they converge.
- The process is usually performed piecemeal, as NASA mission science is often unique.
- If all model that link elements could be coupled in a common framework, formulation efficiency and efficacy could be improved.

What If …?



Original artwork by James Keane

- .. there were a framework allowing trades to be explored concurrently?
  - This is already done for engineering in Team X.
  - Every subsystem has its own technical and cost model.
  - Cost, mass and power for the system is solved in parallel.
- What is missing?
  - Instrument functional models (instrument requirements to observables)
  - Observational models (mission requirements to observables)
  - Science inversion models (observables to physical parameters/results).
  - Hypothesis test frameworks (physical parameters to objectives/conclusions).
- A Digital Twin framework?

"Where is the wisdom we have lost in knowledge?
Where is the knowledge we have lost in information?"

Choruses, by T. S. Eliot

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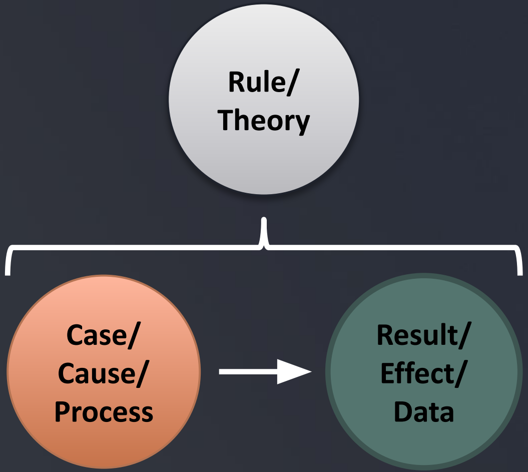
This work was carried out at the California Institute of Technology, Jet Propulsion Laboratory.

Scientific logic: Deduction, induction and abduction

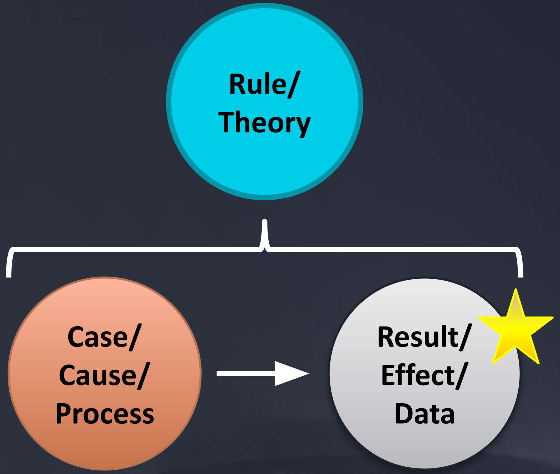
Further reading:
https://www.innovativepolicysolutions.org/articles/from-first-principles-to-theories-revisiting-the-scientific-method-through-abductive-deductive-and-inductive-reasoning
Based on Peirce's theory of inquiry: C. S. Peirce (1878), Deduction, Induction & Hypothesis, *Pop. Sci. Monthly*, 13: 470-482

Induction: Given causes and effects, induce the rules. *Possibilities.*



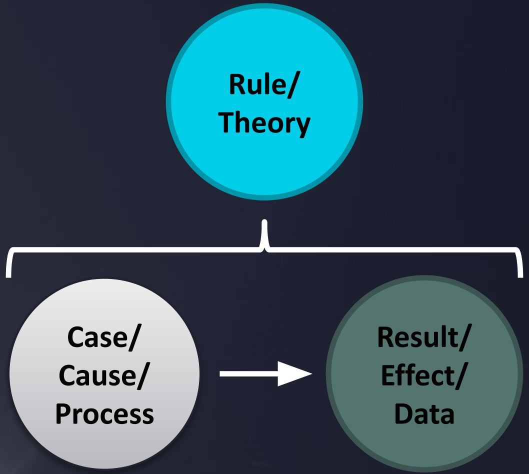
Induction: Given processes and associated observations, formulate theories *based on experience*.

Deduction: Given rules and causes, deduce the effects. *Certainties.*



Deduction: Given theory and possible processes (hypotheses), predict observations.

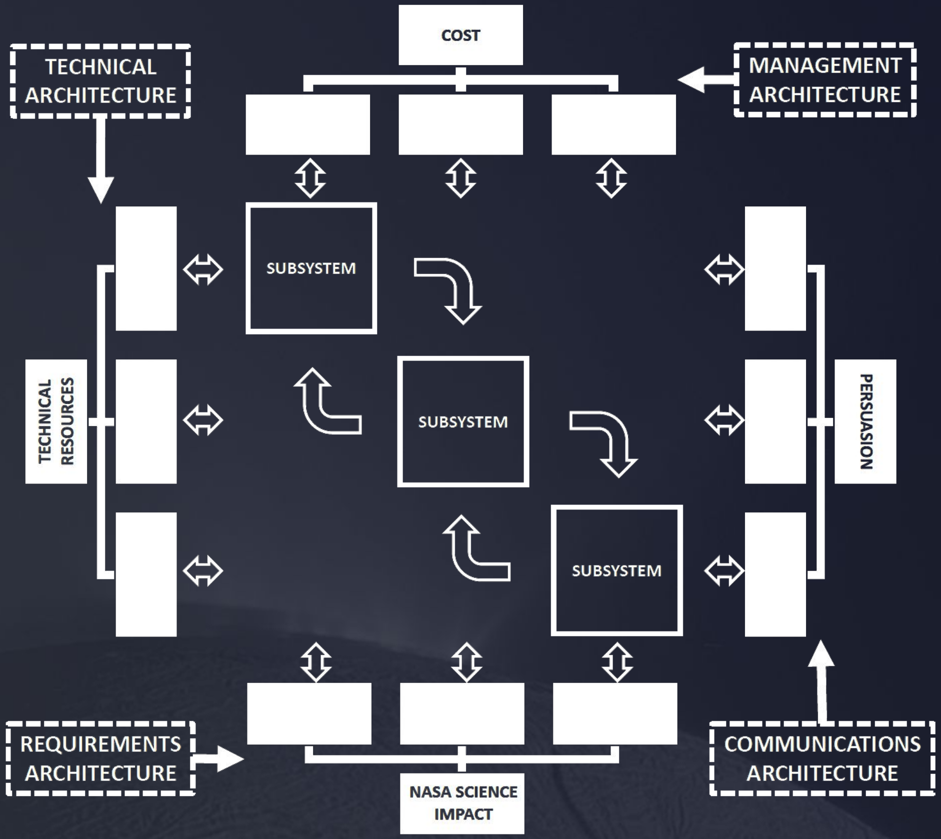
Abduction: Given rules and effects, abduce a cause. *Probabilities.*



Abduction: Given observations in the context of theory, establish the *most likely* causative processes.

Principle trade space dimensions for approvability

- When your approach breaks (hollow arrows), look at the choices you are making (boxes - design), and at the choices that brought you there (branches - architecture).
- EXAMPLE: Your system cannot downlink all the data collected over the course of a day. You could upgrade the radio, add an instrument data compression, and/or revisit your sampling requirements



Science-engineering collaboration:

- Open dialog
  - Build awareness of different disciplines & perspectives
  - *Limitation: Many learn best from doing, not talking*
- Cross-training
  - Co-operative, authentic team-building activities
  - Mentor scientists in engineering roles and vice-versa
  - *Limitation: Needs large activities led by skilled instructors*
- Team integration
  - Scientists embedded in engineering teams and vice versa
  - Project Scientist and Systems Engineers
  - Authority to mediate and influence working practices
  - *Limitation: Key roles require skill and experience*