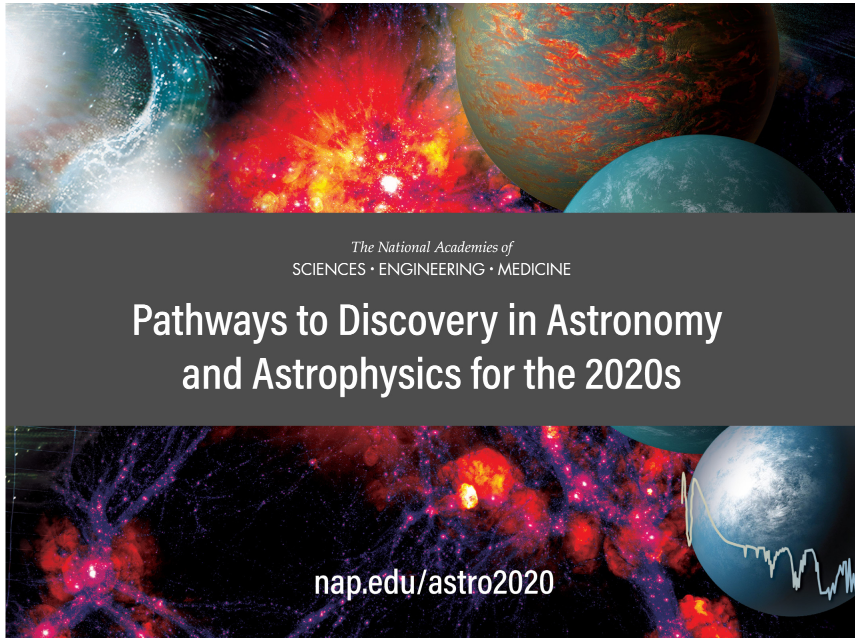


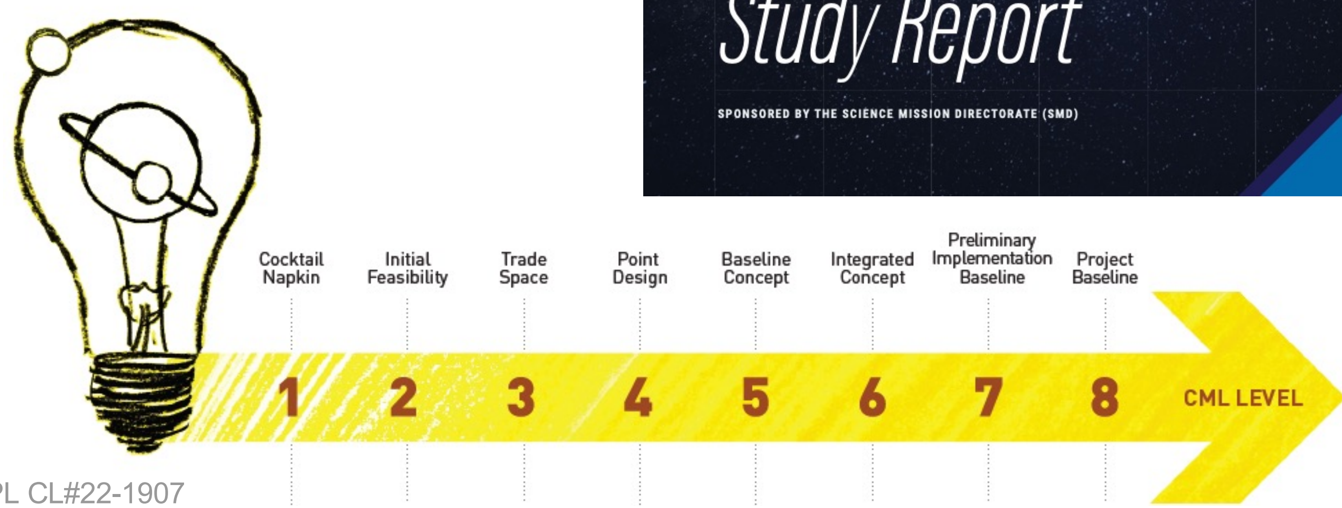
NASA Mission Development 101

John K. Ziemer
Habitable Worlds Observatory, Technical Assessment Group Co-Chair

Significant Contributions from:

Kelley Case, Alfred Nash, and Randii Wessen
JPL Innovation Foundry
https://jplfoundry.jpl.nasa.gov

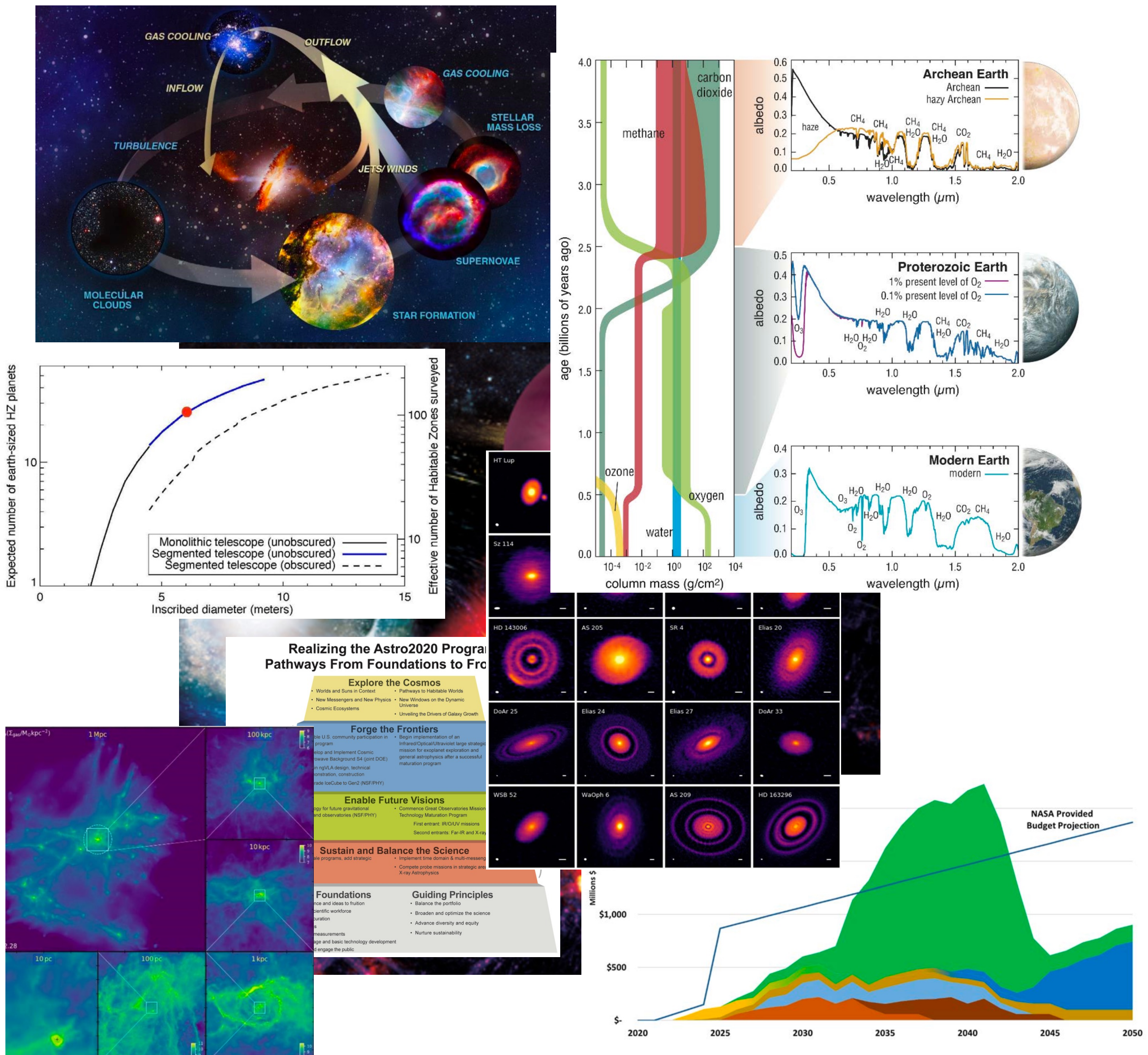
Large Mission Study Team
NASA Science Mission Directorate



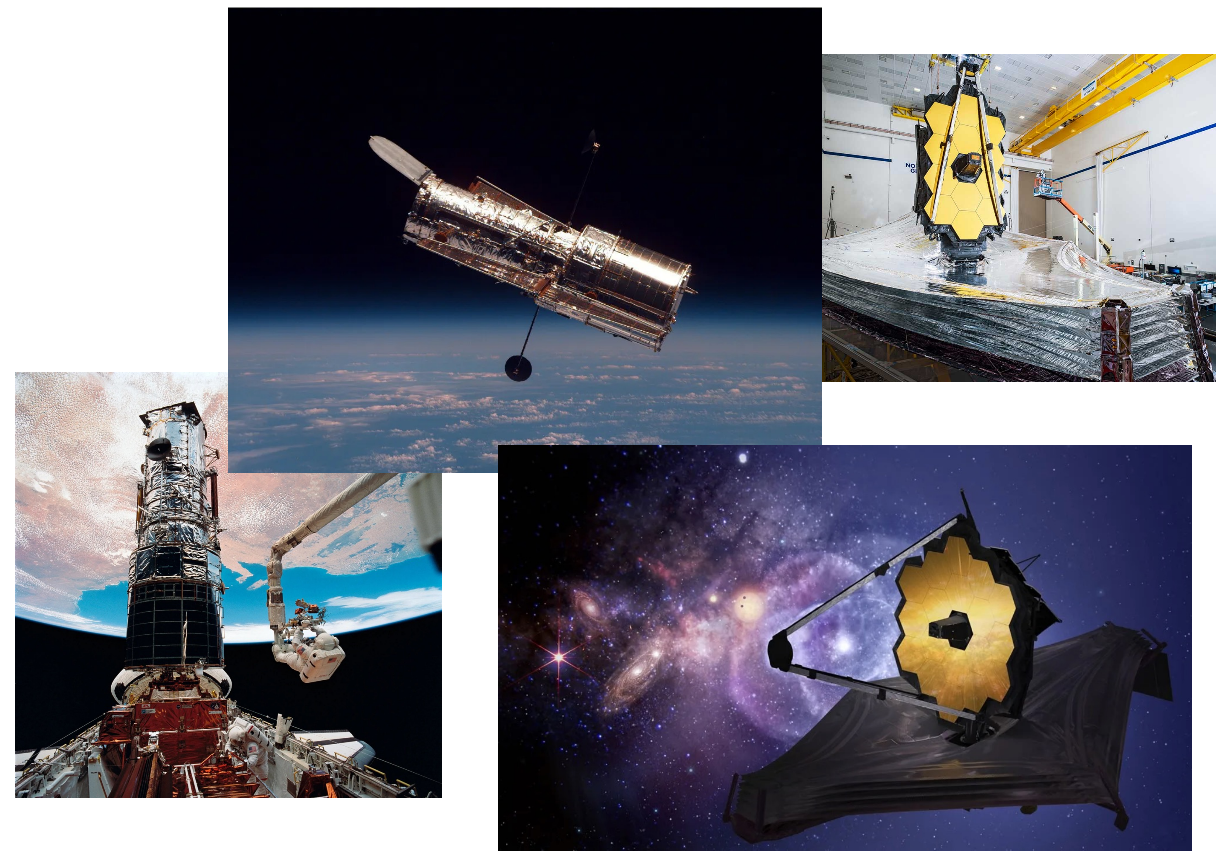
Jet Propulsion Laboratory
California Institute of Technology

JPL CL#22-1907

How do we go from this…



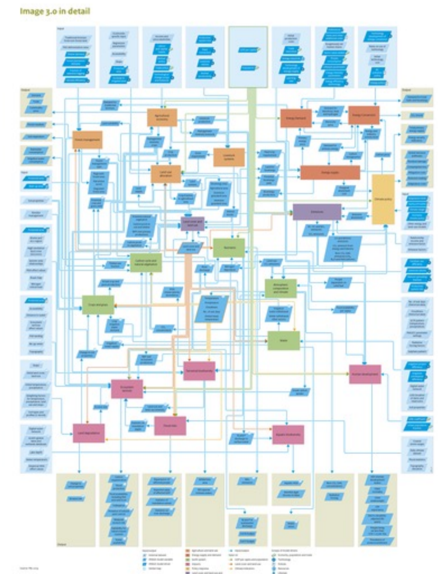
to this?

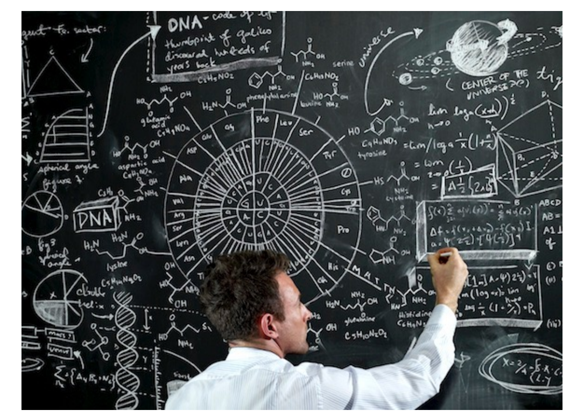


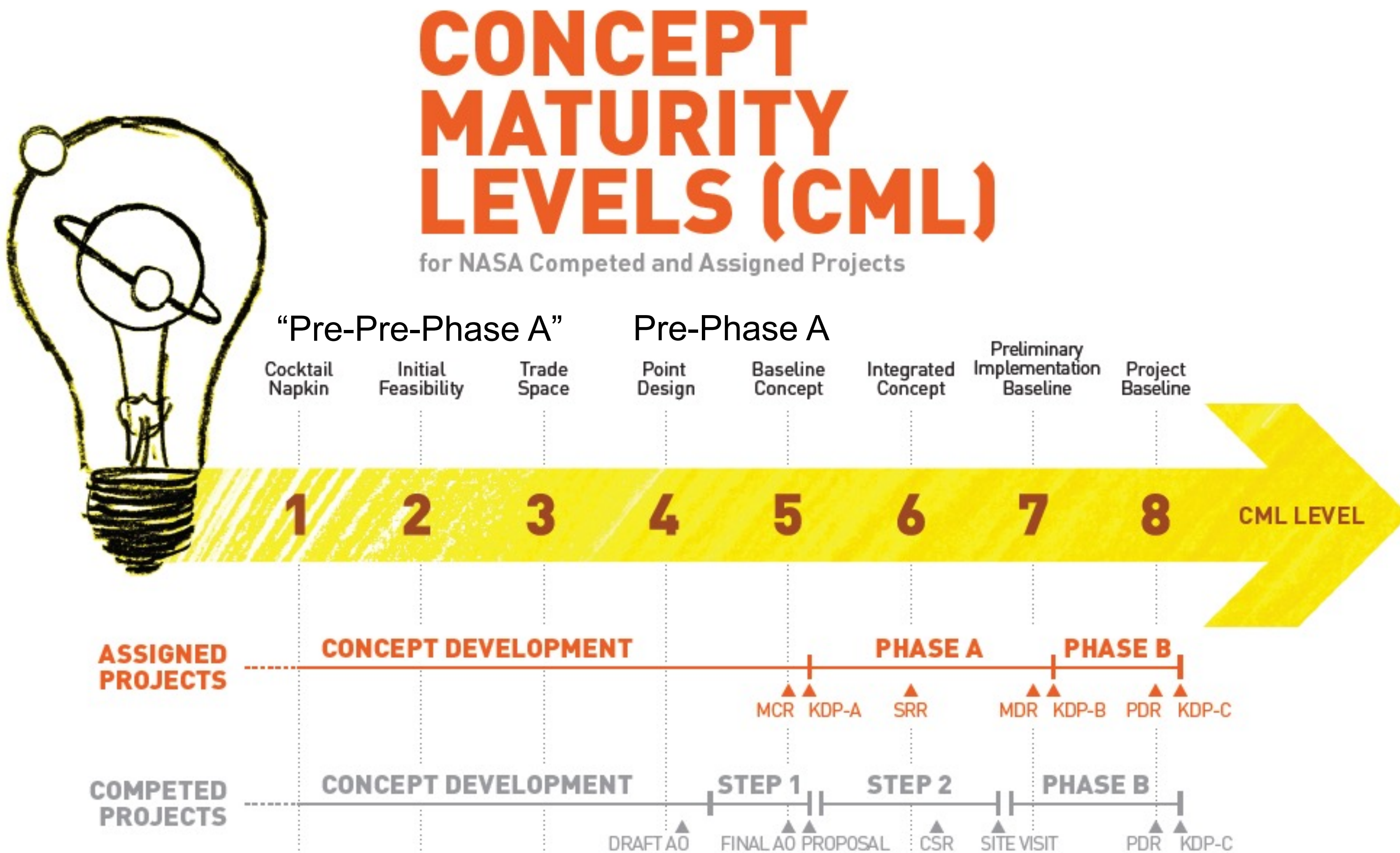
This document has been reviewed and determined not to contain export controlled technical data.

Without these challenges getting in the way!

- No best practices for formulation (prior to Phase A)
- Isolated design in complex systems forming silos
- Too much detail in some areas, not enough in others
- Teams jump to a point-design without truly exploring the trade space



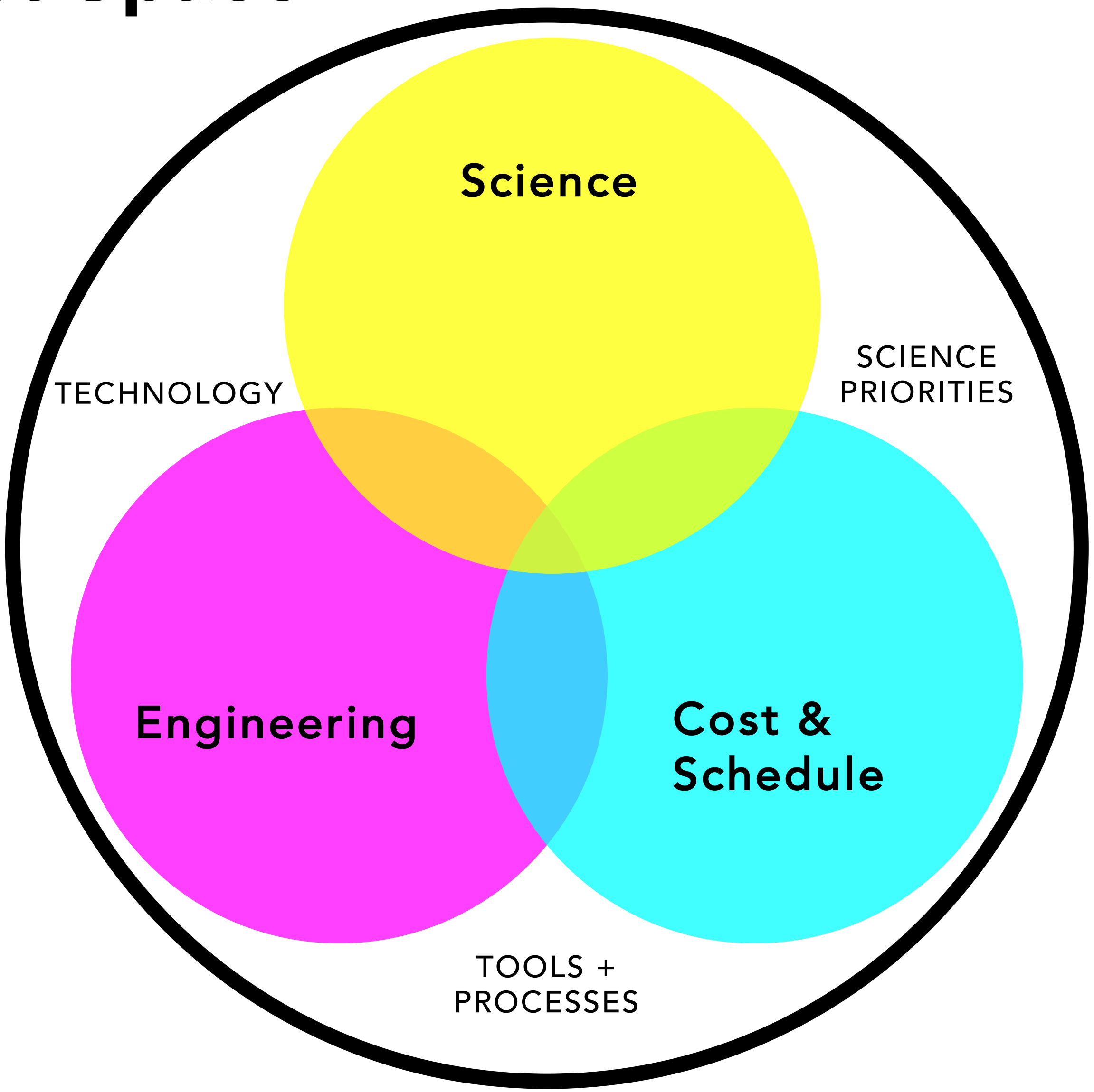




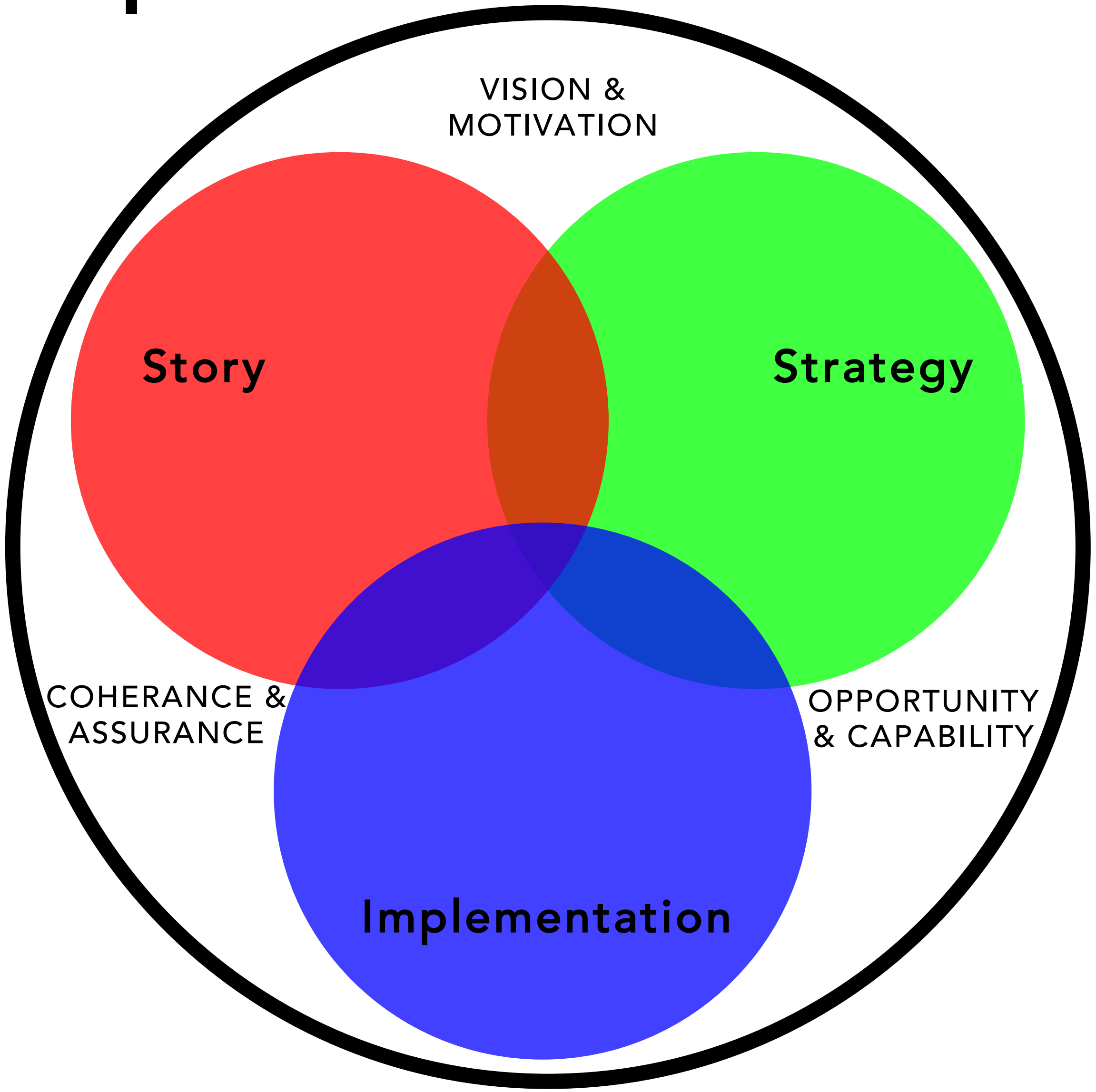
CL# 13-4156; See Refs. [2-5]

- The Concept Maturity Levels (CMLs) were developed to help guide concept teams through formulation progression, before Phase A to the Preliminary Design Review (PDR)
- NASA agrees to cost and scope at Key Decision Point (KDP)-C, right after PDR, but there are many steps along the way – even in pre-pre-Phase A!
- Pre-Phase A ends at KPD-A; we should be at CML 5 before the Mission Concept Review (MCR) – hopefully before the next Decadal Survey

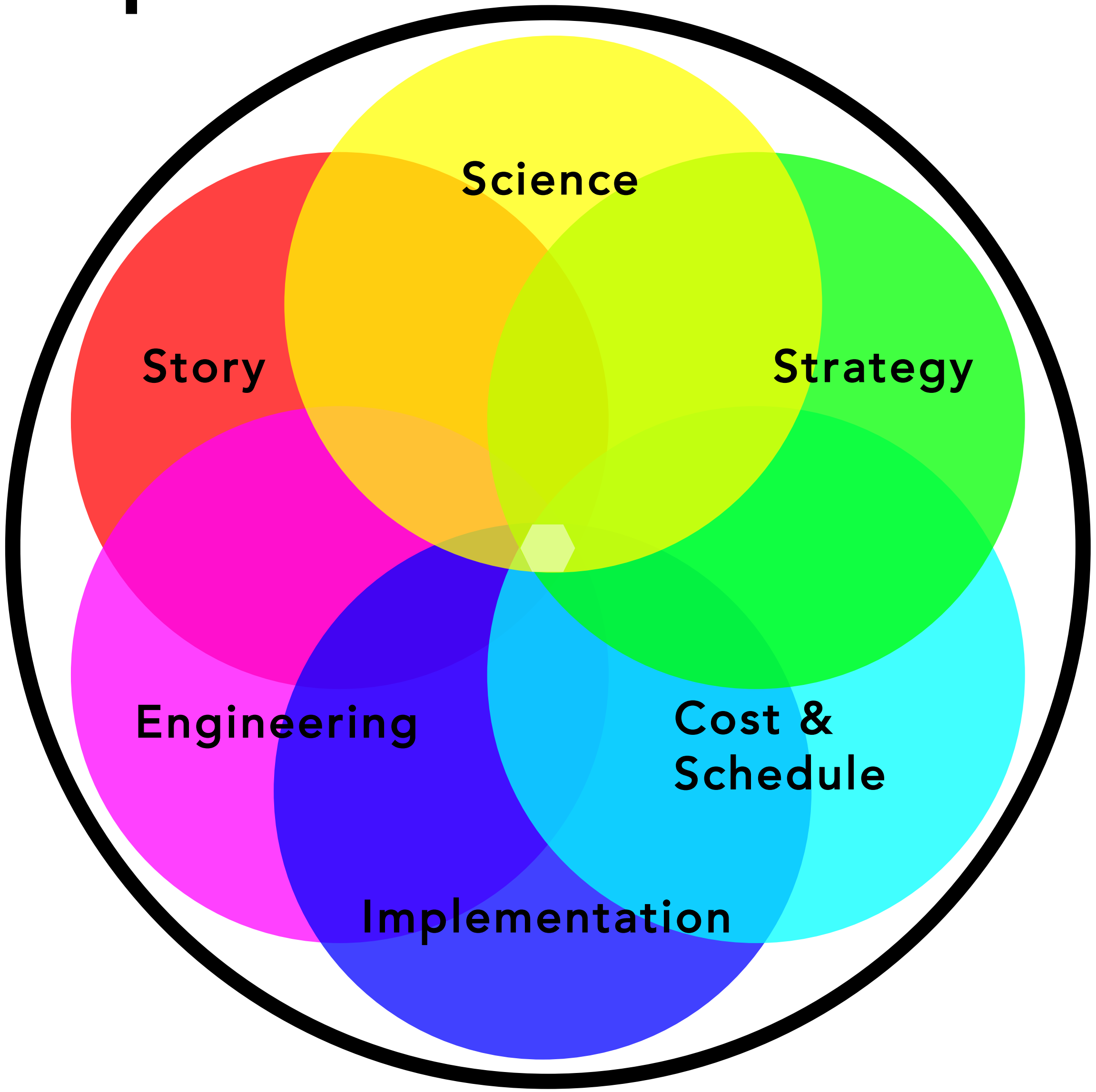
Concept Space



Concept Space



Concept Space



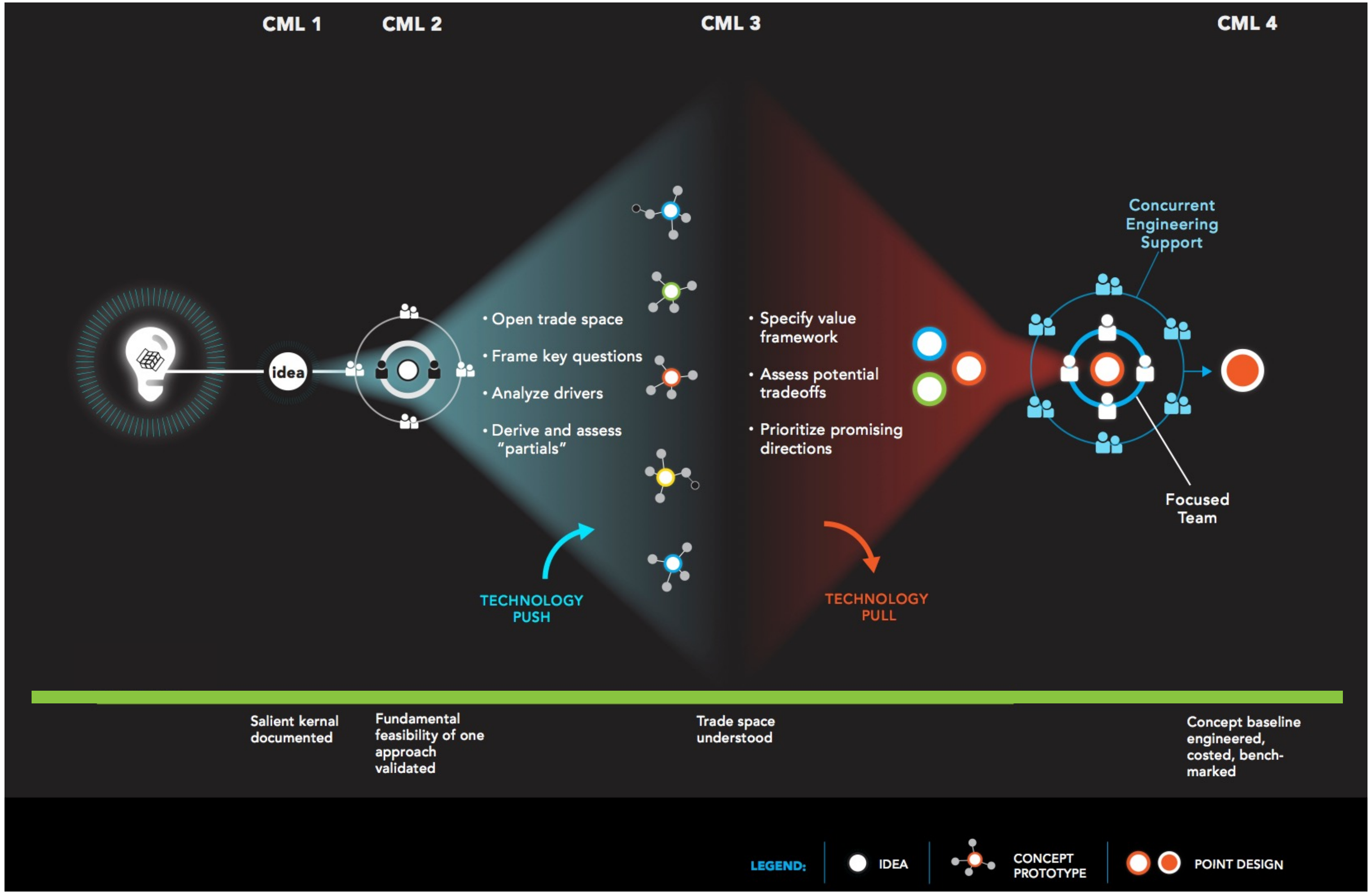
Research
Guide
Create
Question
Explore
Stretch
Narrate
Test
Discover
Evaluate
Reveal
Materialize

The Six Dimensions of Concept Maturity

Taken from Ref. 5

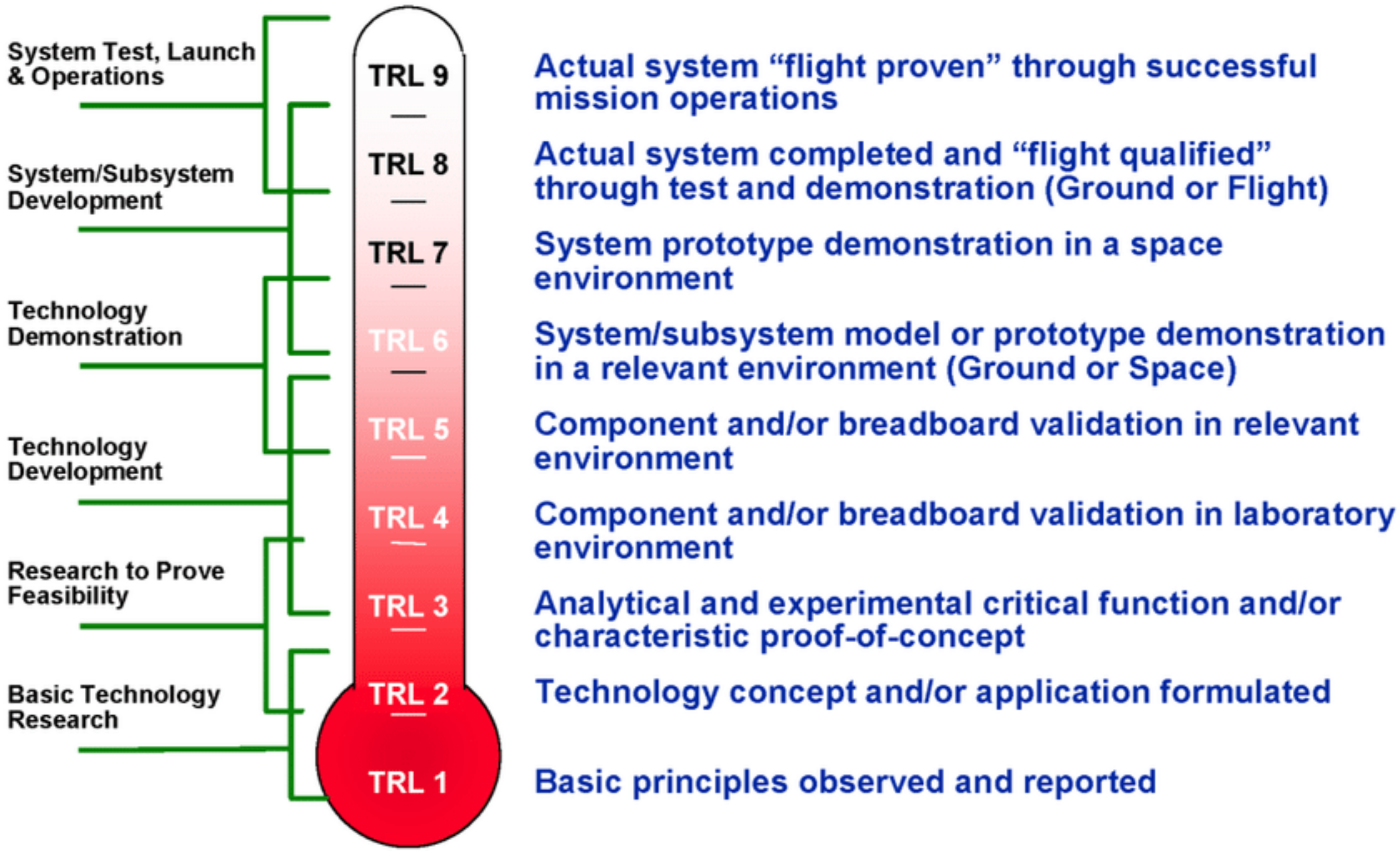
- Using CMLs helps concept teams understand the work that needs to be done in parallel during pre-Phase A
    - The Large Mission Study Report recommended using CMLs and SMD is studying how they can be incorporated into NASA’s practices
- Each of the six dimensions of concept maturity has its own set of expected status and evidence at each CML
- If any one dimension gets ahead or is not connected to the others, ideas and requirements can become “locked in” too early, causing rework

Exploring the Trade Space Through CMLs



- Prior to Phase A (CML 1 - 4)
  - Requirement analyses and architecture trades will be conducted to quantify science in comparison to cost (clearly identifying mission requirements)
  - Descope options will be developed and documented during Pre-Phase A and evaluated at KDP-A to determine realism and feasibility of options
  - Program Office will ensure that independent assessments of architecture trades and descope options are conducted
- At KDP-A (CML 5)
  - Pre-Phase A architecture trades and descope options will be evaluated at KDP-A for assessment of mission concept maturity, technology maturity, risks, cost and schedule realism, and project maturity, to enable the making of early decisions and programmatic adjustments

How does technology readiness align to concept maturity?



NASA Technology Readiness Levels.
With Unicorns.

Created by Grant Tremblay

We once spent two hours arguing whether one component on an instrument concept* was Technology Readiness Level 3 or 4. During that meeting, I wrote this. It became popular at NASA HQ and JPL and, on request, I later refined it into this.

This page serves as a living repository for the only mildly popular thing I've ever done.

NASA Technology Readiness Levels

TRL 1: What if there were Unicorns

TRL 2: We have drawn a Unicorn

TRL 3: `unicorn_v8_final_final.cad`

TRL 4: We have placed a horn on a horse in our lab

TRL 5: We took the horse outside

TRL 6: We're now calling the horse a Unicorn

TRL 7: We're pretty sure the Unicorn might survive if we launch it into space

TRL 8: omg it survived

TRL 9: Our reference design incorporates high-heritage Space Unicorns

Do CMLs and TRLs align?

- There is no strict alignment between CMLs and TRLs, except possibly NASA's requirement of reaching TRL 6 by PDR (CML 8); however:
- NASA Large Mission Study suggests that technologies need to be matured earlier in the project lifecycle, TRL 6 by end of Phase A (CML 7) and possibly ***TRL ≥5 by the start of Phase A (CML 5)***
- To explore the trade space (CML 3), we must have at least a proof-of-concept with an analytical model of expected performance (TRL ≥3)
- Once we move to a point design (CML 4) and specify key performance requirements, work should focus on demonstrating performance (TRL ≥4)
- The problem with this alignment is timing: technologies can take years to move up one TRL, while concepts can be explored much more quickly, moving up one CML in less than a year

How do we know we are done exploring the trade space?

We understand and can communicate:

- What ideas were considered, what was not studied, and why
- Key sensitivities – what happened when key parameters were varied
- Benefits and risks of each approach

This includes documenting:

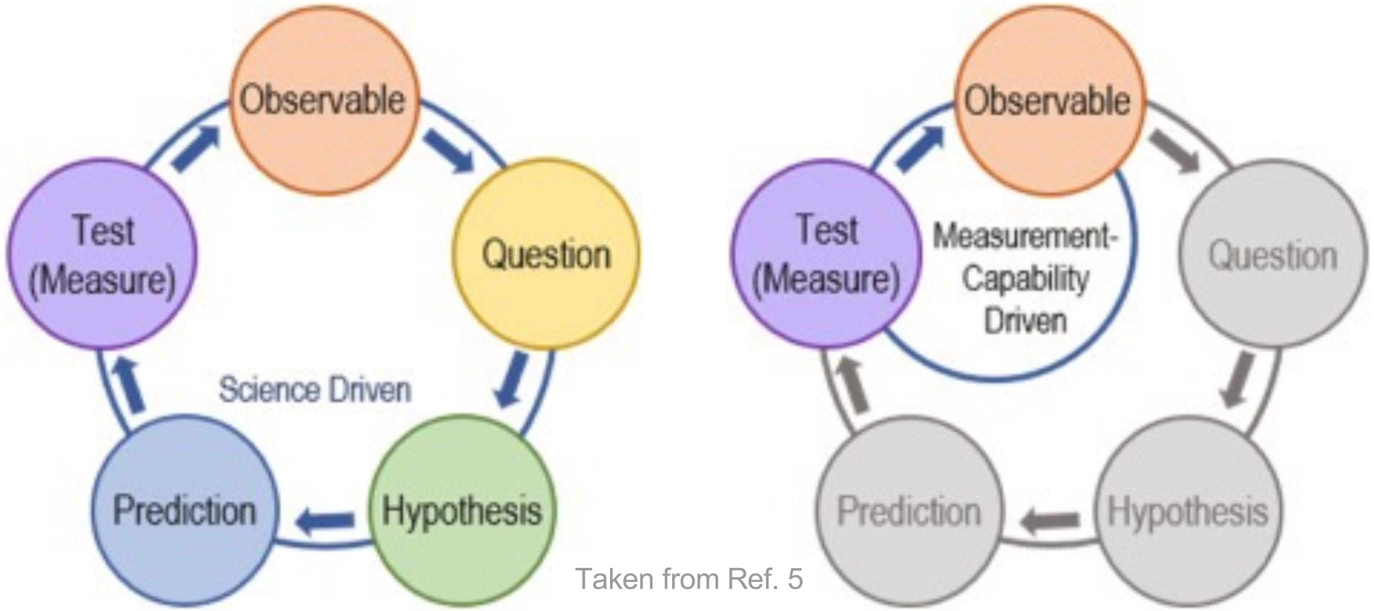
- The "soft spots" unique to the concept (worthy of priority in-depth study)
- The “threshold” for an acceptable part of the concept to move onto the next step of development
- What technology, science, and programmatic advancements could change the space and merit further investigation

Science Traceability: Going from Goals to Requirements

- **Goals**: These come from NASA and the Decadal Survey, often verbatim and always at a high level
- **Questions**: These come from science communities (i.e. ExEP Science Gap List) and help focus the science investigation
- **Objectives**: A concrete statement of what the science investigation will achieve and / or the hypotheses to be tested
- **Observables**: The physical quantities and parameters that need to be observed (i.e. spectral lines, feature sizes, etc.)
- **Measurements**: What actually will be measured or detected, including any precision or accuracy requirements

- As we go from left to right, the details of ***and the rationale for*** the investigation are captured; we move from goals to requirements, causes to effects, and we provide focus
- Each progression requires models of the science (both expected conditions and behavior), experiment / measurement, and observatory / instrument performance
- We cannot skip any step – we must know the rationale as part of developing the requirements to effectively design the investigation and observatory

Science in Early CMLs



Taken from Ref. 5

Developing early CML science cases is an iterative process, balancing our ambitions to discover and explore the universe within the reality of limited capabilities and resources

- For the best exploration of the trade space, science driven investigations address a specific question with testable hypotheses / predictions
  - They provide the rationale and help us derive science-driven requirements
  - We may not be able to completely answer the question or address all the hypothesis due to other constraints, but we can get a sense of science return vs. capability (usually model based)
- Science investigations based purely on measurement capability can be open ended, but hard for the rest of the concept team to derive requirements
  - We need to be able to have “discovery space”, but when are we good enough?
  - Pushes the capability to the limit of what’s feasible (often hard to know!)

Science vs. Implementation Trade Space

Science must inform mission architectures and trades with the goal of reducing mission design and development cost, scope, and risk where possible vs. quantified science return – find the science return gradient.

- At CML 3, we look for the *partials* or gradient of the quality of the science returned by the mission vs. some measurement parameter (i.e. bandwidth, resolution, etc.) that impacts the mission architecture
- For science, we would always like to have better and more capability – but how does the science return really depend on the measurements?
- We can build off a threshold or minimum science return, and then quantify the advantage of having even more capability
- This is often model based, but we need to quantify input and output uncertainties along with parameter sensitivities to be most useful

Looking at all 6-dimensions of CML 3

Area	CML 3 (Trade Space) Goals
Science	Goals, objectives are linked to specific investigations, each with a range of acceptable physical parameters and observables, including precision/accuracy needs; potential threshold(s) identified as well as improvements obtained vs. measurements (the “partials” or *science return gradient*)
Engineering	Trade options explored at the element level, including the “what” and “how” (e.g., instruments, platforms, ground stations, etc.) down to subsystem level as necessary (WBS Level 3); contingencies and margins on key technical resources and performance predictions are quantified with at least 50% confidence. Potential risks are identified and prioritized.
Implementation	Potential partners are identified and made part of analysis team, if possible; implementation options are considered and documented with each trade.
Cost	Cost is estimated at WBS Level 2/3 based on parametric models, if they apply. Cost drivers are identified and gradients vs. system performance parameters are calculated, if possible.
Story	Preliminary story (e.g., central arguments, ideas, draft graphics) created with the compelling nature and scientific priority of the proposed investigation’s science goals and objectives made clear.
Strategy	Customers are identified, along with needs and wants for each; strengths, weaknesses, opportunities and threats are identified for each architecture option

Some Last Notes on Early CMLs

- Work includes both expanding and contracting, building off what has been done before, but allowing for new advancements and ideas
  - We are definitely in the expansive phase, but not unconstrained
- We start with the science and technology, but all parts of the concept need to mature together in parallel
  - Resist jumping to a point design or baseline too early – very challenging!
  - Understand the driving parameters and sensitivities in the design, which requires system models of the science, observatory, data processing, etc.
- It is an iterative process – get ideas out there early and test them
  - To enable discovery, we need to know our desires, capabilities and constraints
  - Prototyping ideas early helps us find the relations between science, engineering, and cost along with what models we need to evaluate options

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

Acronyms

- AO Announcement of Opportunity
- APD Astrophysics Division
- CML Concept Maturity Level
- CSR Concept Study Report
- KDP Key Decision Point
- MCR Mission Concept Review
- MDR Mission Definition Review
- PDR Preliminary Design Review
- SMD Science Mission Directorate
- SRR System Requirements Review

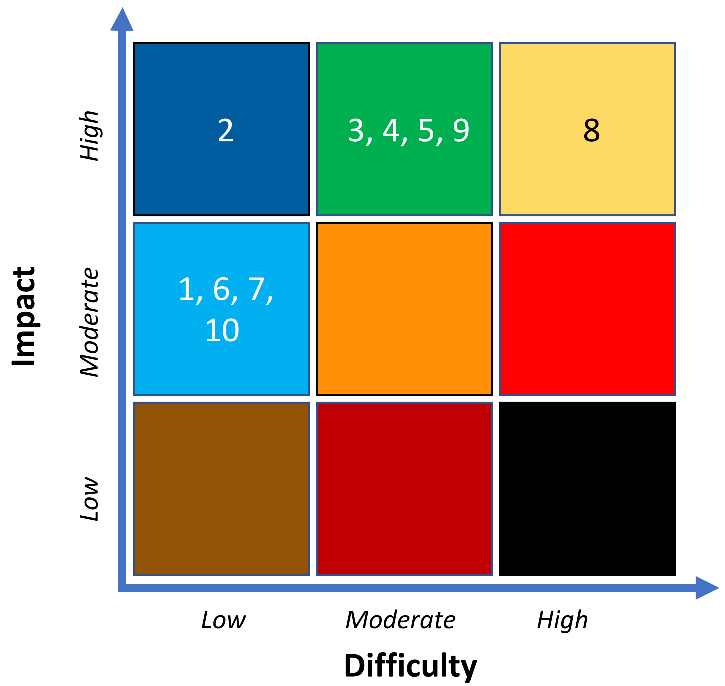
References

1. National Academies of Sciences, Engineering, and Medicine 2021. ***Pathways to Discovery in Astronomy and Astrophysics for the 2020s***. Washington, DC: The National Academies Press. https://doi.org/10.17226/26141.
2. R. Wessen, C.S. Borden, J.K. Ziemer, R.C. Moeller, J. Ervin, J. Lang, ***Space mission concept development using concept maturity levels***, in: AIAA Space 2013 Conference and Exposition, 2013, p. 5454. https://doi.org/10.2514/6.2013-5454.
3. K. Case, A. Nash, R. Wessen, J. Ziemer, ***The six dimensions of mission concept formulation***, in: SECESA 2016, 2016. Madrid, Spain, October 5-7, 2016.
4. J.K. Ziemer, R.R. Wessen, P.V. Johnson, ***Exploring the Science Trade Space with the JPL Innovation Foundry A-Team***, Journal of Concurrent Engineering, 26(1) 2018: 22-32. https://doi.org/10.1177/1063293X17740406.
5. Wessen, R. R., Propster, P., Cable, M., Case, K., Guethe, C., Matousek, S., Nash, A., Ziemer, J. (2022). ***Developing compelling and science-focused mission concepts for NASA competed mission proposals***. Acta Astronautica, 191, 502-509. https://doi.org/10.1016/j.actaastro.2021.12.002.
6. NASA SMD***, Large Mission Study Report***, https://science.nasa.gov/science-red/s3fs-public/atoms/files/SMD_LMS_eBook_report2.pdf, October 2020.
7. NASA APD, 2020 Decadal Survey Planning, Large Mission Concept Studies Final Reports, https://science.nasa.gov/astrophysics/2020-decadal-survey-planning.
8. Kepner, C.H. and Tregoe, B.B., ***The Rational Manager***, 1965.
9. Blackwood, G., ***Choosing the Future: The Kepner-Tregoe Matrix for Complex Trades,*** presentation and recording available at https://exoplanets.nasa.gov/exep/technology/tech_colloquium/, Feb. 28, 2022.

Backup Charts

Recommendations from the SMD Large Mission Study

Classification of Recommendations from the Large Missions Study



No.	Recommendation Title
1	*Pre-Phase A Team Composition*
2	*Pre-Phase A Architecture Trades and Descope Options*
3	*System Maturity Assessment*
4	*Technology Integration into Complex Systems*
5	*Analytical Tools*
6	*Cost and Schedule Estimation*
7	*Standing Review Boards (SRBs)*
8	*Instrument Selection Process*
9	*SMD Capabilities*
10	*Center Capabilities*

Taken from SMD “Large Mission Study Report” presentation, see Ref. [6] and link.

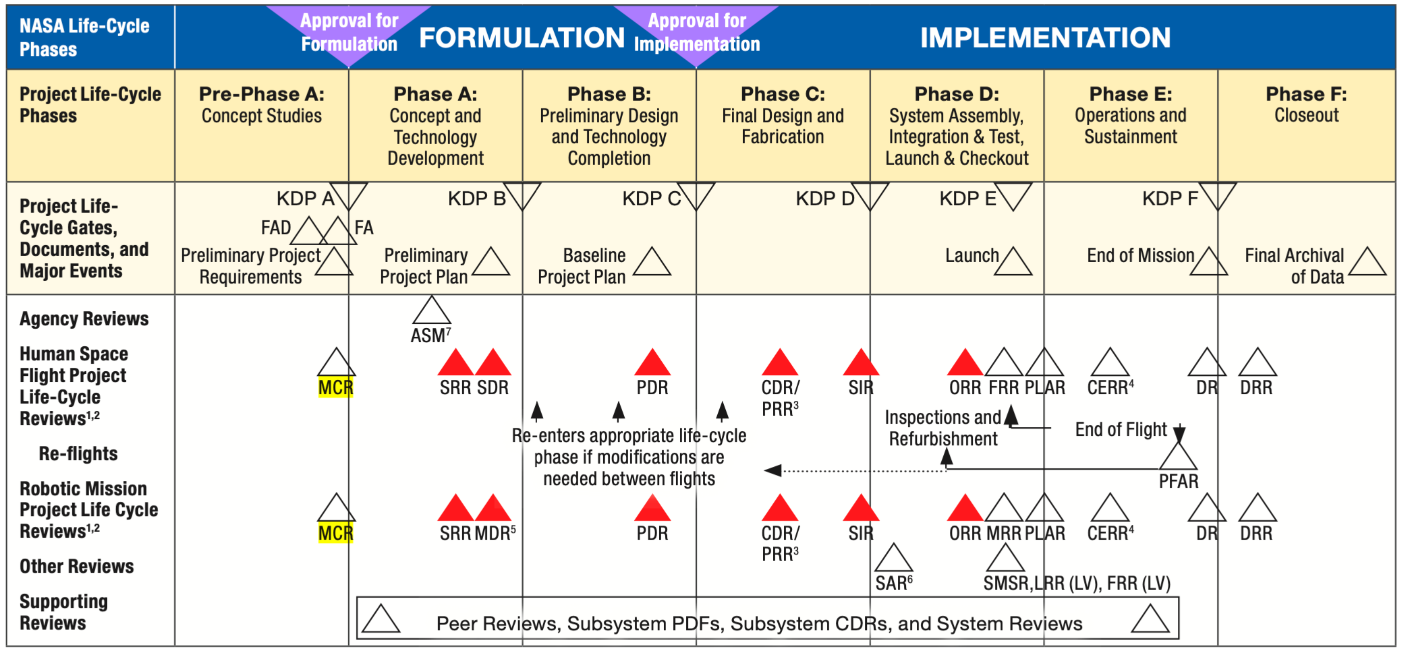
SMD Recommendation Disposition

Bottom Line Up Front – SMD Large Missions Study Implementation Plan

No.	Large Missions Study Recommendation	Disposition	Large Missions Study Implementation Plan
1	*Pre-Phase A Team Composition*	Accept	Staffing will be based on needed skill sets and expertise (not based on availability of personnel). An Agency-wide search shall be conducted, followed by a nationwide search, if needed
2	*Pre-Phase A Architecture Trades and Descope Options*	Accept	Program Office will conduct independent assessment of Pre-Phase A architecture trades and descope options for evaluation at KDP-A. Implementation effective immediately.
3	*System Maturity Assessment*	Accept w/Follow-Up	Further action is required. A team, sponsored by the SMD DAA/P and led by the SMD Chief Engineer, will be formed for further investigation.
4	*Technology Integration into Complex Systems*	Partially Accept	Mandate increased scrutiny of technology maturity at reviews and KDPs. Implementation effective immediately. Further action is required - A strategic approach will be developed by the SMD Chief Technologist to identify technology needs and funding sources for technology development.
5	*Analytical Tools*	Partially Accept	Large strategic missions will incorporate common tool sets, when possible, and establish an agreed margin and risk philosophy with partners and providers early in the life cycle.
6	*Cost and Schedule Estimation*	Accept	Life cycle cost estimates shall be communicated in terms of bins for Pre-Phase A and ranges for Phases A and B to set external expectations. Implementation effective immediately.
7	*Standing Review Boards (SRBs)*	Accept	The SMD policy of convening the SRBs prior to MCR, and when required, convening of the Independent Review Boards (IRBs), has already been implemented. Initiating SRB kickoff meetings.
8	*Instrument Selection Process*	Partially Accept w/Follow-Up	Further action is required. A team led by the SMD Deputy AA for Research will be established. Modification of SMD policy may be required.
9	*SMD Capabilities*	Accept	Program Offices of large missions will be adequately staffed early in pre-formulation in order to perform programmatic assessments and oversight. Implementation effective immediately.
10	*Center Capabilities*	Accept	SMD and Centers have ownership and accountability of large strategic missions and will work closely to identify and solve problems. Implementation effective immediately.

The SMD Large Missions Implementation Plan will require an intentional shift in how we approach the development of our missions

NASA Flight Project Life Cycle



FOOTNOTES

1. Flexibility is allowed as to the timing, number, and content of reviews as long as the equivalent information is provided at each KDP and the approach is fully documented in the Project Plan.
2. Life-cycle review objectives and expected maturity states for these reviews and the attendant KDPs are contained in Table 2-5 and Appendix D Table D-3 of this handbook
3. PRR is needed only when there are multiple copies of systems. It does not require an SRB. Timing is notional.
4. CERRs are established at the discretion of program .
5. For robotic missions, the SRR and the MDR may be combined.
6. SAR generally applies to human space flight.
7. Timing of the ASM is determined by the MDAA. It may take place at any time during Phase A.

▲ Red triangles represent life-cycle reviews that require SRBs. The Decision Authority, Administrator, MDAA, or Center Director may request the SRB to conduct other reviews.

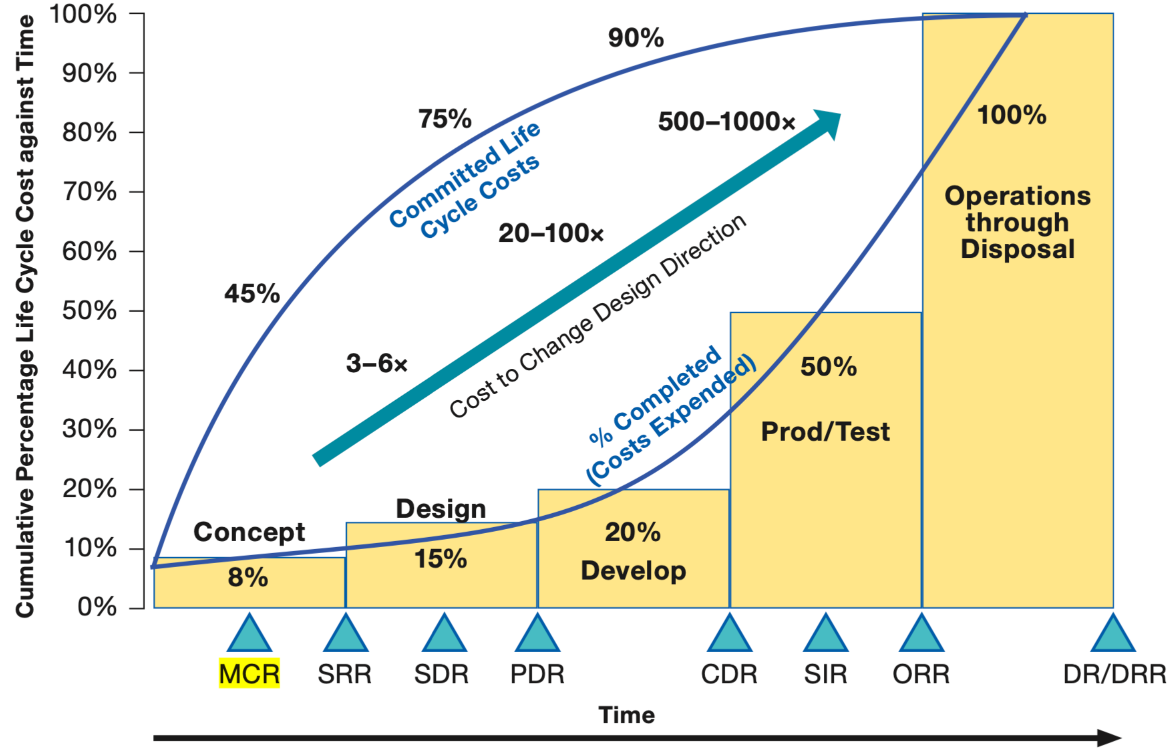
ACRONYMS

ASM – Acquisition Strategy Meeting
CDR – Critical Design Review
CERR – Critical Events Readiness Review
DR – Decommissioning Review
DRR – Disposal Readiness Review
FA – Formulation Agreement
FAD – Formulation Authorization Document
FRR – Flight Readiness Review
KDP – Key Decision Point
LRR – Launch Readiness Review
LV – Launch Vehicle
MCR – Mission Concept Review
MDR – Mission Definition Review
MRR – Mission Readiness Review
ORR – Operational Readiness Review
PDR – Preliminary Design Review
PFAR – Post-Flight Assessment Review
PLAR – Post-Launch Assessment Review
PRR – Production Readiness Review
SAR – System Acceptance Review
SDR – System Definition Review
SIR – System Integration Review
SMSR – Safety and Mission Success Review
SRB – Standing Review Board
SRR – System Requirements Review

FIGURE 3.0-1 NASA Space Flight Project Life Cycle from NPR 7120.5E

Taken from NASA Systems Engineering Handbook, https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf

Mission Life Cycle Cost vs. Time



MCR	Mission Concept Review	**CDR**	Critical Design Review
SRR	System Requirements Review	**SIR**	System Integration Review
SDR	System Definition Review	**ORR**	Operational Readiness Review
PDR	Preliminary Design Review	**DR/DRR**	Decommissioning/Disposal Readiness Review

Adapted from INCOSE-TP-2003-002-04, 2015

Taken from NASA Systems Engineering Handbook, https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf

CML's Provide a Framework for Understanding a Concept's Maturity

CML 1 *Cocktail Napkin* - The science questions have been well articulated, the type of science observations needed for addressing these questions have been proposed, and a rudimentary sketch of the mission concept and high-level objectives have been created. The essence of what makes the idea unique and meaningful have been captured.

CML 2 *Initial Feasibility* – The idea is expanded and questioned on the basis of feasibility, from a science, technical, and programmatic viewpoint. Lower-level objectives have been specified, key performance parameters quantified and basic calculations have been performed. These calculations, to first-order, determine the viability of the concept

CML 3 *Trade Space* - Exploration has been done around the science objectives and architectural trades between the spacecraft system, ground system and mission design to explore impacts on and understand the relationship between science return, cost, and risk

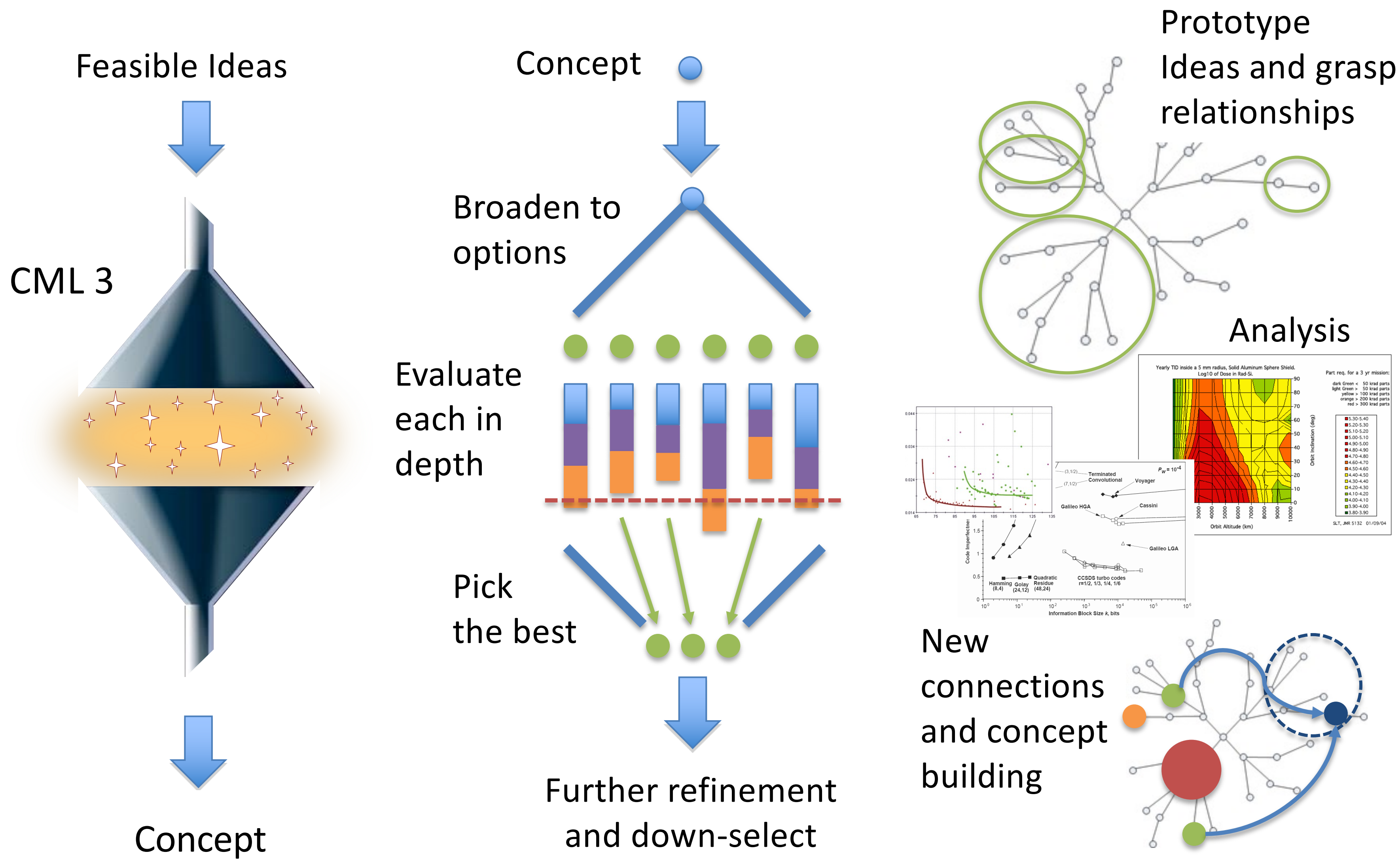
CML 4 *Point Design* – A specific design and cost that returns the desired science has been selected within the trade space and defined down to the level of major subsystems with acceptable margins and reserves. Subsystems trades have been performed.

CML 5 *Baseline Concept* - Implementation approach has been defined including partners, contracting mode, integration and test approach, cost and schedule. This maturity level represents the level needed to write a NASA Step 1 proposal (for competed projects) or hold a Mission Concept Review (for assigned projects)

Best Practices for Advancing CMLs

- Many, many different ways of progressing through CMLs
- My “Top 10” keys to success / best practices:
  - A well connected, diverse team of experts, across all 6 CML dimensions
  - Experienced leadership and inclusive mentorship with intentional feedback
  - A well defined, open process (i.e. criteria) that is communicated early-on
  - Stay focused on sharing, use the best tools for team access to latest data
  - Allow multiple cycles of prototyping ideas: create / test / learn / teach
  - Scrutinize ideas, not people – respectful questioning and active listening
  - Keep it at the right level: start high, dive deep, then come back up again
  - Set deadlines and don’t let any dimension of the concept get too far behind
  - Understand risks and uncertainties – be honest and quantitative
  - Document the outcome and rationale outward to build consensus

How does CML 3 Work?



CML 3 / 4 Science Focus

Area	CML 3 (Trade Space)	CML 4 (Point Design)
Science Scope	Very broad in nature; potential hypothesis tests and discovery space identified including thresholds or “cliffs”	Down-select to a set of science objectives that can be achieved within the observatory’s capabilities
Science Traceability	Goals, objectives are linked to specific investigations, each with a range of acceptable physical parameters and observables	Complete draft of a Science Traceability Matrix (STM), including measurement and instrument requirements necessary to achieve each science objective
Science Return	Attempt to quantify science return for each investigation	Specify preliminary science mission baseline and one threshold for each point design
Science Models	Physics-based models are identified and used to explore options and predicted outcomes; potential confounding variables and observables are identified	Science models are linked to observatory performance models to derive a coherent set of requirements; uncertainty is quantified
Science Data	Science data volumes are considered as well as the beginnings of science data pipelines	Science data system and ground data system are sized to match science requirements

CML 3 / 4 Engineering Focus

Area	CML 3 (Trade Space)	CML 4 (Point Design)
Engineering Scope	Multiple element options are explored down to subsystem level (Level 3 WBS, i.e., 05.01, 05.02, etc.) or component level only when necessary	Point design specified at WBS Level 3, subsystem level with trades completed for key lower-level components (i.e. technology)
Technology Impact	Technologies are examined that can improve science return; performance models are used to understand advantages while maturity is evaluated to determine risks	Specific technologies that are required for the point design are identified along with key performance parameters the technology must meet to behave as expected in the system
Requirements	Potential driving requirements are identified; All element-level engineering technical resource margins (e.g., volume, mass, power, ΔV, data rates, data volumes) are positive, after contingencies	Driving requirements are quantified; All preliminary subsystem-level engineering technical resource margins (e.g., volume, mass, power, ΔV, data rates, data volumes) are positive, after contingencies
Performance	Performance is quantified with better than 50% confidence for each architecture / element / subsystem option	Performance is quantified with better than 70% confidence down to subsystem level (component level where necessary)