National Aeronautics and Space Administration

# Model Based Systems Engineering

## Using Maxwell's Demon to Tame the "Devil in the details" that are encountered during System Development

GSFC Systems Engineering Seminar

October 10, 2017

Model Based Systems Engineering

# James Clerk Maxwell

June 13, 1831 – November 5, 1879

- A Scottish scientist in the field of mathematical physics
- His most notable achievement was to formulate the classical theory of electromagnetic radiation, bringing together for the first time electricity, magnetism, and light as manifestations of the same phenomenon.
- Maxwell's equations for electromagnetism have been called the "second great unification in physics" after the first one realized by Isaac Newton.
- Maxwell's work on thermodynamics led him to devise the thought experiment that came to be known as Maxwell's demon, where the second law of thermodynamics is violated by an imaginary being capable of sorting particles by energy.

Entropy is often equated to disorder or uncertainty

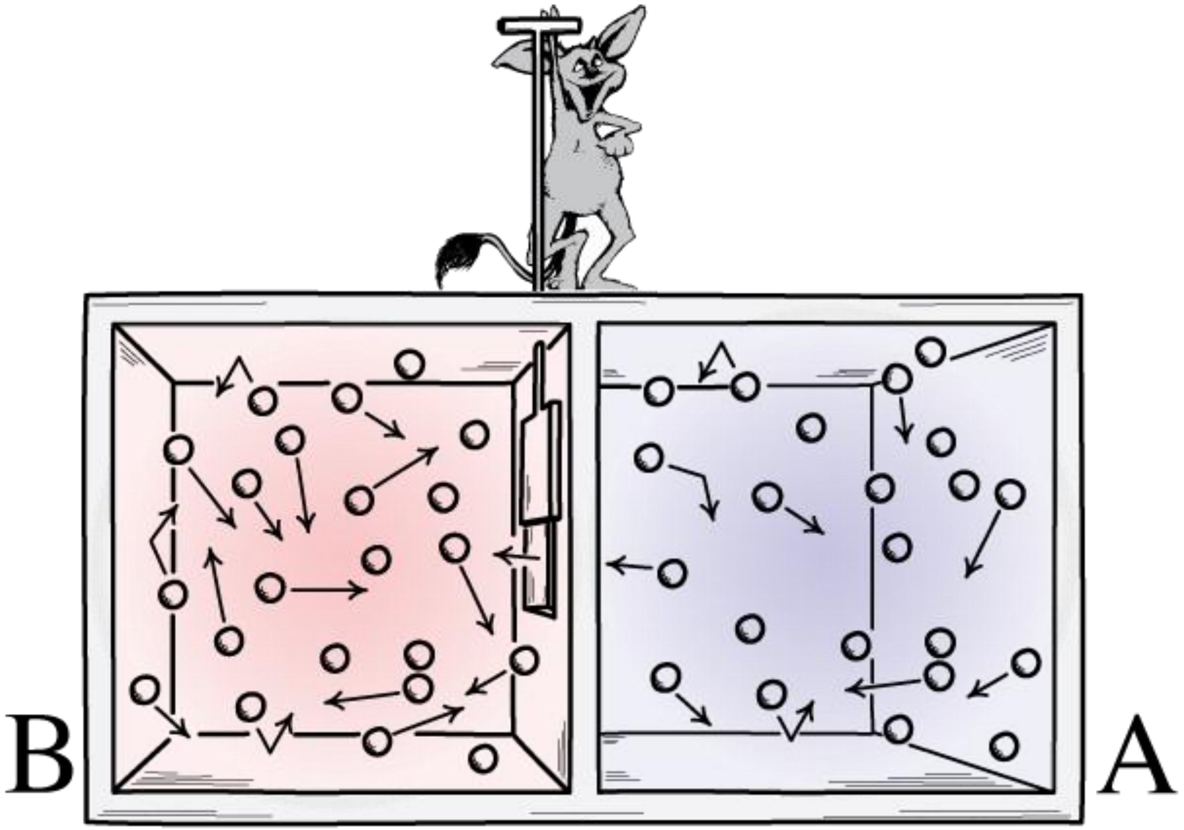
$$S = -k_B \sum_i p_i \ln p_i$$

$p_i$ = Probability of occurring in state i

# Maxwell’s Demon

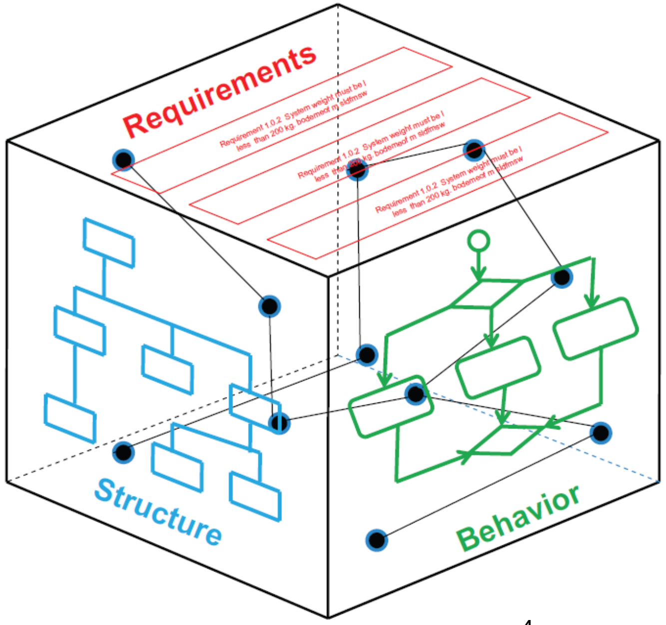
For more than 140 years Maxwell’s demon has intrigued, enlightened, mystified, frustrated, and challenged physicists in unique and interesting ways.

- First appeared in a letter to a friend in 1867.
- Published in his book "Theory of Heat" in 1871.
- Term "demon" coined by Lord Kelvin (William Thompson) in 1874.
- "demon" really meant mediating, not devilish.
- Continually under debate by famous physicists.
- **Still debated today**.



# So, what does that have to do with Systems Engineering?

Model-Based Systems Engineering (MBSE): The **formalized application of modeling** to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases”




A system model: **An information management system** that represent a physical system, through a **cohesive, rigorous and unambiguous interrelationship** between system structure, behaviors and requirements.

Can better knowledge of the system enable the reduction of its ‘entropy’?

# A Case for Change: Science Mission Directorate[1]

- **This science-driven technology development** not only enables scientific leadership, it also feeds an innovation engine with **impacts** that are **well beyond** the realm of the **initial question** and application space.

- **Broad and lasting impacts are not coming from playing it safe**, they come from ambitious science driving innovative technology. Note that we have a NASA science program that has a variety of tools with different objectives. But, **when it comes to breakthrough science, playing it safe intellectually does not cut it!**

- Final point: **intellectual ambition is not proportional to the cost of a system**. In fact, the most entrepreneurial solutions are the ones that **pair intellectual ambition with nearly impossible financial constraints!**

Performing Science isn't getting any easier!

OSIRIS-REx, JWST, MMS, WFIRST, PACE/OCI are some of the most complex and ambitious science missions ever!

1 Dr. Thomas Zurbuchen: https://blogs.nasa.gov/drthomasz/2017/02/13/ambitious-science-driving-innovative-technology/

# A Case for Change: OCE SE Capability Leadership[2]

**Systems Engineering Tech Fellow convened a small group of expert NASA engineering practitioners to understand if and where opportunities exist within systems engineering.**

**Culture of compliance**

- **Failure is not an option, … even when it's acceptable given a project's risk classification (balance between ALL vs. Catastrophic?)**

**Workforce experience**

- **Losing our in-house systems/hardware development capability**
- **Technical leadership is the capstone of engineering the system**
- **SE is a broad and ambiguous term, … who really is an SE and what are they responsible, … process, technical decisions, both?**

**Process proliferation**

- **Magnitude of policy is overwhelming… (agency, center, orgs, etc.)**
- **Experienced engineers need minimal policy… others "cookbook" it**

SE Environment within NASA may have opportunity for improvement

2 NASA SE Technical Fellow: 2017 SE Capability Leadership Team Face to Face

# A Case for Change: Clear and compelling communication[3]

**When engineering analyses and risk assessments are condensed to fit on a standard form or overhead slide, information is inevitably lost.**

- **"In the process, the priority assigned to information can be easily misrepresented by its placement on a chart and the language that is used."**
- **…also criticized the sloppy language on the slide. "The vaguely quantitative words 'significant' and 'significantly' are used 5 times on this slide"**
- **[with respect to inconsistent use of 3 cubic inches] …While such inconsistencies might seem minor, in highly technical fields like aerospace engineering a misplaced decimal point or mistaken unit of measurement can easily engender inconsistencies and inaccuracies.**
- **As information gets passed up an organization hierarchy, from people who do analysis to mid-level managers to high-level leadership, key explanations and supporting information is filtered out.**

Sound Engineering is based upon rigor and clarity

3 Columbia Accident Report, p. 191

# A Case for Change: JPL Systems Engineering; Five System Engineering Challenges[4]

1. **Mission complexity is growing faster than our ability to manage it…increasing mission risk from inadequate specification & incomplete verification**

2. **System design emerges from the pieces, not from an architecture…resulting in systems which are brittle, difficult to test, and complex and expensive to operate.**

3. **Knowledge and investment are lost at project lifecycle phase boundaries…increasing development cost and risk of late discovery of design problems.**

4. **Knowledge and investment are lost between projects…increasing cost and risk; damping the potential for true product lines**

5. **Technical and programmatic sides of projects are poorly coupled…hampering effective project decision-making; increasing development risk.**

SE needs to evolve to meet the demand

4 *JPL Internal IOM 3100-09-040, T Bayer, 24 Oct 2009*

# A Case for Change: GSFC Systems Engineering[5]

**The current environment**

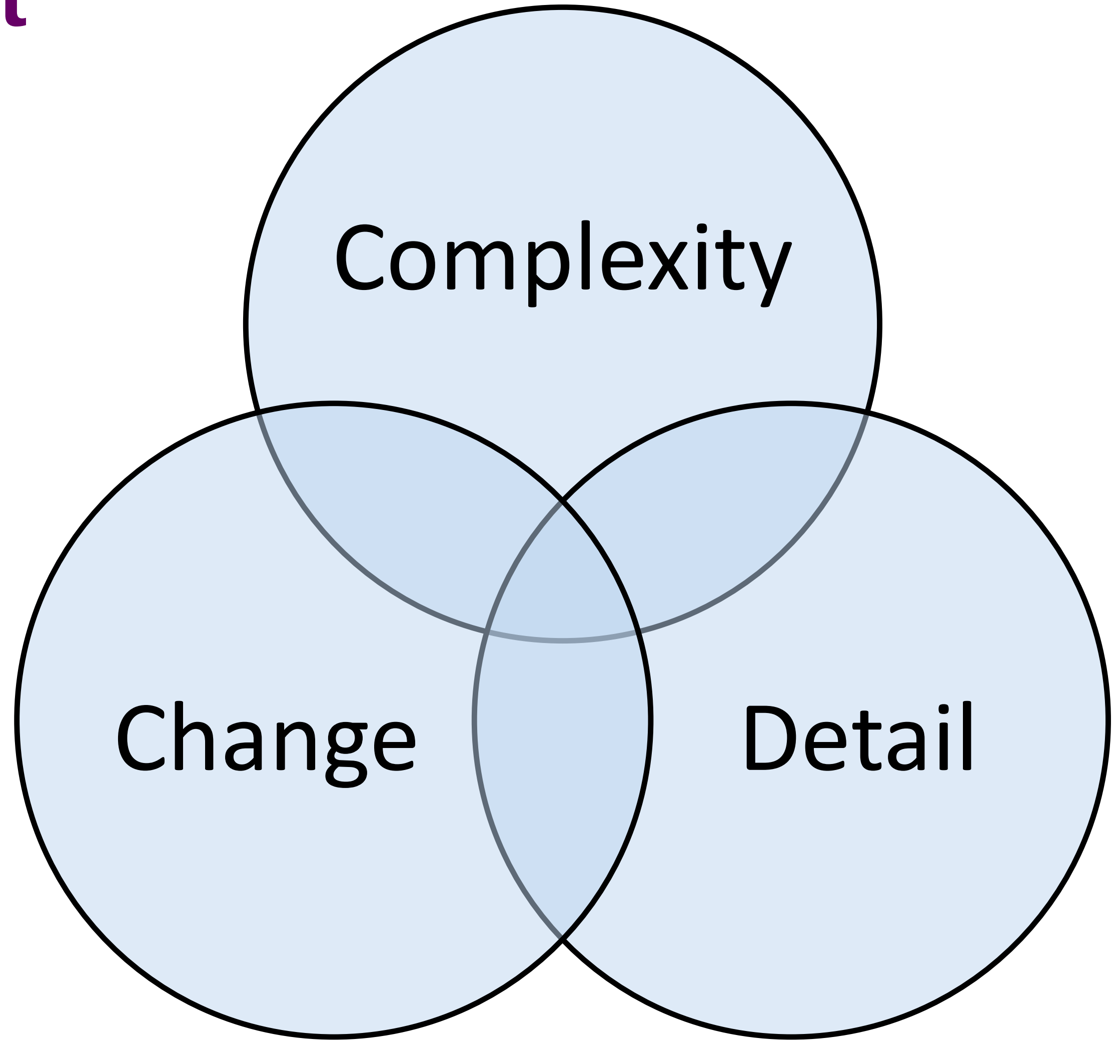
- **Full lifecycle support for NASA missions**
- **Some of the most difficult technical engineering ever**
- **Ambitious science, coupled with more tighter control increases pressure for both proposal development and implementation**
- **Difficulty for contractor community to fully respond to need**
- **Must find ways to do more with less, even as we work to grow the workforce and improve tools/methods**

SE needs to evolve to meet the demand

5 Observations from an Assistant Branch Head

# Systems Engineering environment

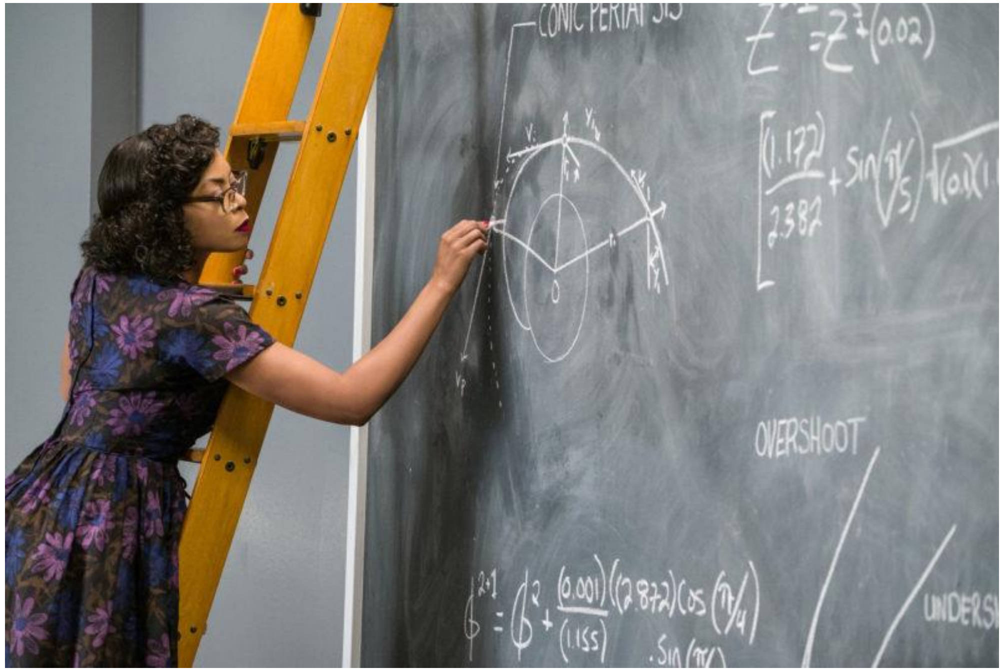
| SE Role | SE Responsibility |
|---|---|
| Leadership | Find the right system solution |
| | Point everyone to the right solution |
| Management | Forecast |
| | Plan |
| | Coordinate |
| | Command |
| | Organize |
| | Control |

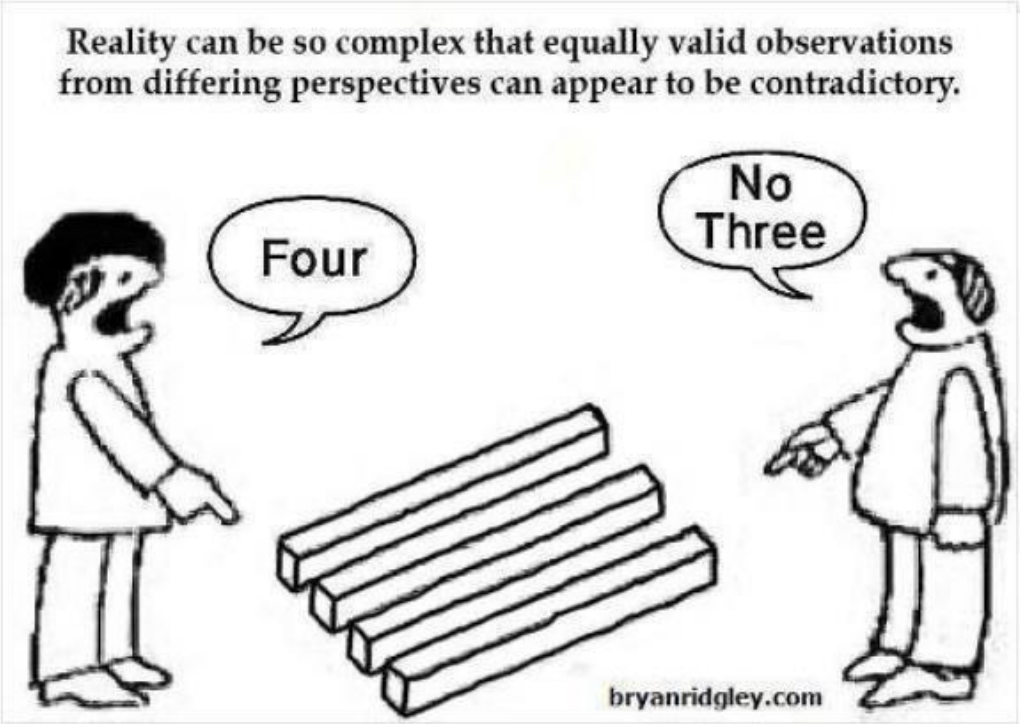


What is complexity?

- A system is said to be "complex" if it is capable of generating unexpected results.

- "Emergence" is the name scientists have given to events that defy scientific laws based on order and stability.



# So, what does that have to do with Systems Engineering?

Managing is hard…

…constant change makes it harder…

Q: Do mistakes happen?

A: Only when:

- System requirements change
- Programmatic factors (Resources, schedule) change
- Personnel change
- Vendors change
- Parts become unavailable
- A new version of information is released

ICD:
~~V1.0~~
~~V1.1~~
~~V1.2~~
V2.1

Space Craft:
~~JPL~~
~~GSFC~~
~~RSDO~~
~~JPL~~
GSFC

Launch:
~~2004~~
~~2008~~
~~2015~~
2017

Destination:
~~Mars~~
~~N.E. Asteroid~~
~~Mars~~
~~Moon~~
Mars

PDL:
~~Bob~~
~~Jane~~
~~Bob~~
~~Sally~~
Ralph

Mounting Material:
~~Carbon~~
~~Aluminum~~
~~Steel~~
Gold

Dictionary.com "the devil is in the details"

- The devil is in the details in **culture**
- The devil is in the **details definition**

- Even the grandest project depends on the success of the smallest components.

- The Wire

Maxwell: …such a being, whose attributes are still as essentially finite as our own, would be able to do what is at present impossible to us.

So…

Can we use knowledge such as Maxwell’s demon possessed to manage complexity, and defeat the Devil in the Details?

Premise: Modeling can definitely help…

- Design systems more rigorously and clearly
- Analyze the System Architecture more readily, respond more readily
- Communicate the system more articulately, both internally and externally
- Automate efforts that are manually performed today.

# Three Examples: Not a Modeling Clinic

| | |
|---|---|
| Model Based Sounding Rocket | • Represents a specific mission from the Sounding Rocket Program (WFF)<br>• Part of OCE MBSE Pathfinder effort<br>• Attempts to create a model that supports the design review (communication) |
| Antenna Deployment | • Case study: Represents an antenna sub-system (IV&V, assurance)<br>• Simulates deployment operation to check logic (Analysis, integration)<br>• Enhanced communication with software team (Communication) |
| MMS mission | • Early FY ‘18 IRAD work to model MMS mission<br>• Growing awareness of model use in early lifecycle<br>• Demonstrates SE analysis (SE Analysis) |

# Three Examples: Take away

## Model Based Sounding Rocket

- Represents a specific mission from the Sounding Rocket Program (WFF)
- SRP/Projects integrate PI needs and instruments into launch vehicles
- Design review case study shows great potential for electronic exploration of the model
  - Navigate conversation in a more agile fashion
  - Immediate access to design information
  - Eliminate RFAs

## Antenna Deployment

- "A day in the life" of a Systems Engineer (IV&V)
- Simulation found error in design logic (confusion introduced by vendor documentation)
- Changed the way SE and Software implementer interacted and coordinated
- Leveraging this learning on WFIRST (Core Flight Executive, Coordinating with 580)

## MMS mission

- Laying a foundation for approaches to be used for missions at GSFC
- Establishing methods for transferring "heritage" design to next generations
- Demonstrates SE analysis (SE Analysis)
- Creates framework for improving cross organizational collaboration (Standards used in architecture)

# Model Based System Development (MBSD) Effort Types Currently On-Going at GSFC

**System Development Process Modeling**

Intent is to create system development tools that will increase the productivity of system engineers.

**Mission Design and Development Modeling**

To provide system engineers with an actual system design modeling language that is capable of defining almost all aspects of a mission design.

These capabilities would produce data oriented products to:

- Enhance the quality and integrity of system designs
- Provide a more integrated and reliable method of transferring development information between organizations, technical and managerial disciplines, and life-cycle phases.

# GSFC MBSD Model Development and Application Vision

**System Development Modeling and Tools**

**Mission Design and Development Modeling**

All Development & Operation Aspects:

- Products (Technical)
- Resources (Project Management)
- Processes (GSFC)

All Life-Cycle Phases:

- Pre-Phase-A
- A, B, C, D, E
- Operations

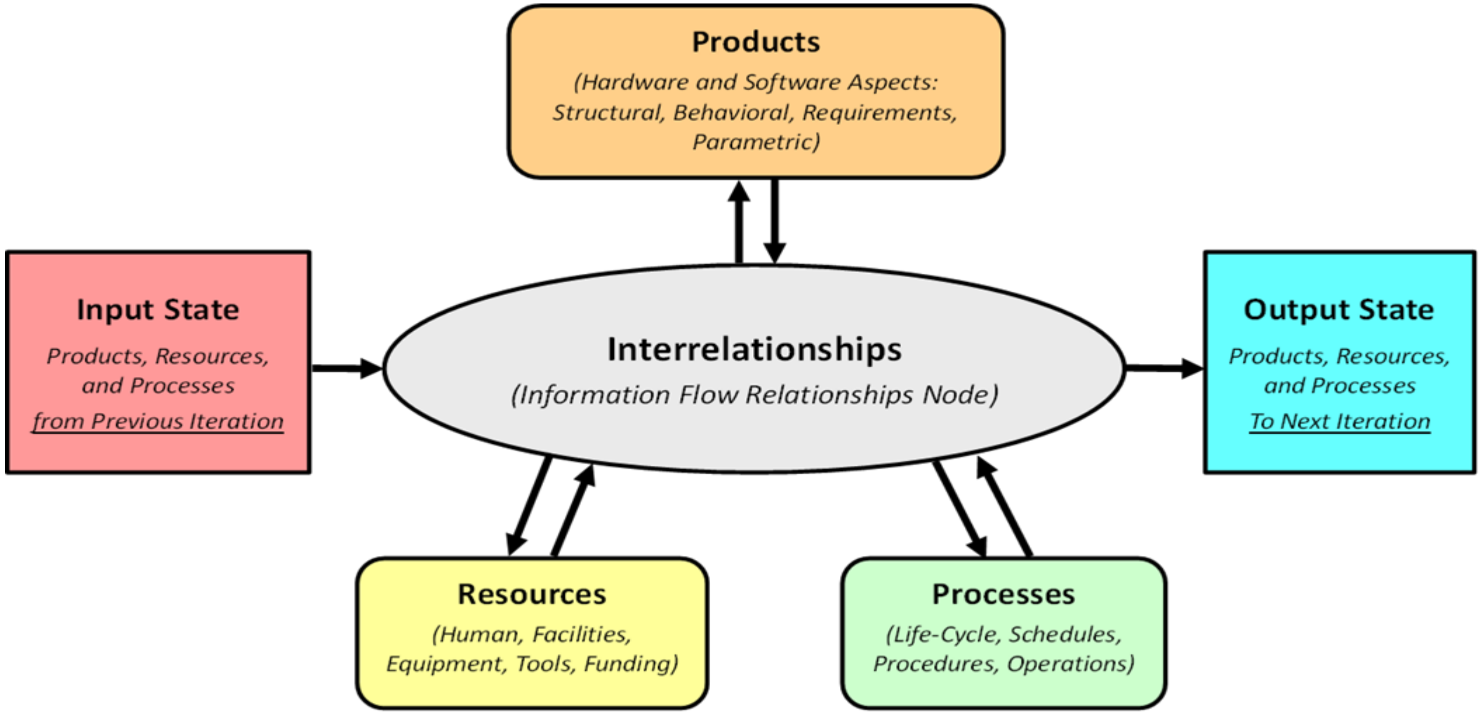
All GSFC Lines of Business

- Astrophysics
- Earth Science
- Heliophsyics
- Planetary Science
- Communications
- Cross-cutting
- Other

# GSFC Model Based System Development Associated Activities

Sounding Rocket Design (FY16-FY18 Pathfinder)

MMS and DSM Mission Design (FY18 IRAD)



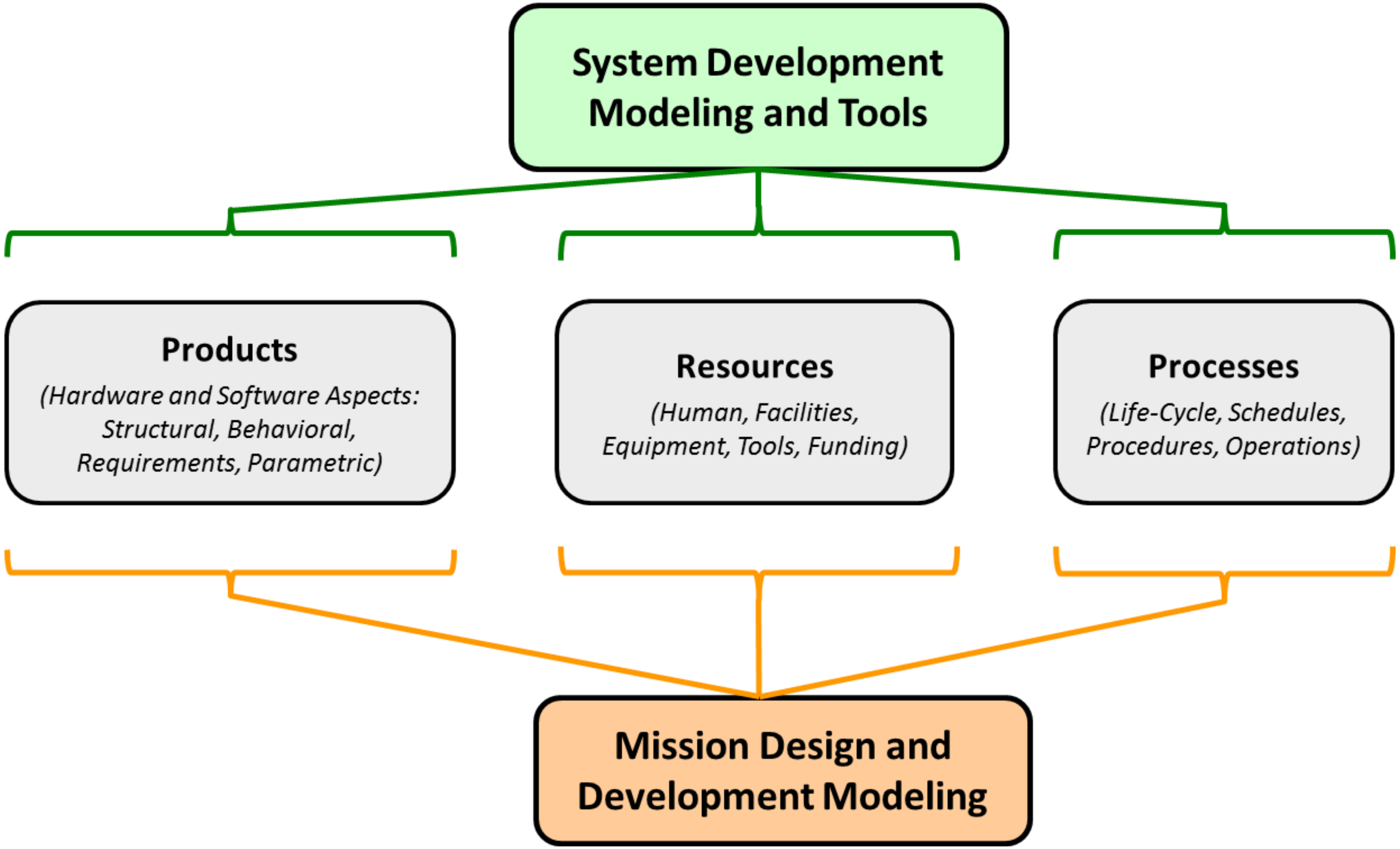

Future Efforts

Sounding Rocket Development Process (FY16-FY18 Pathfinder)

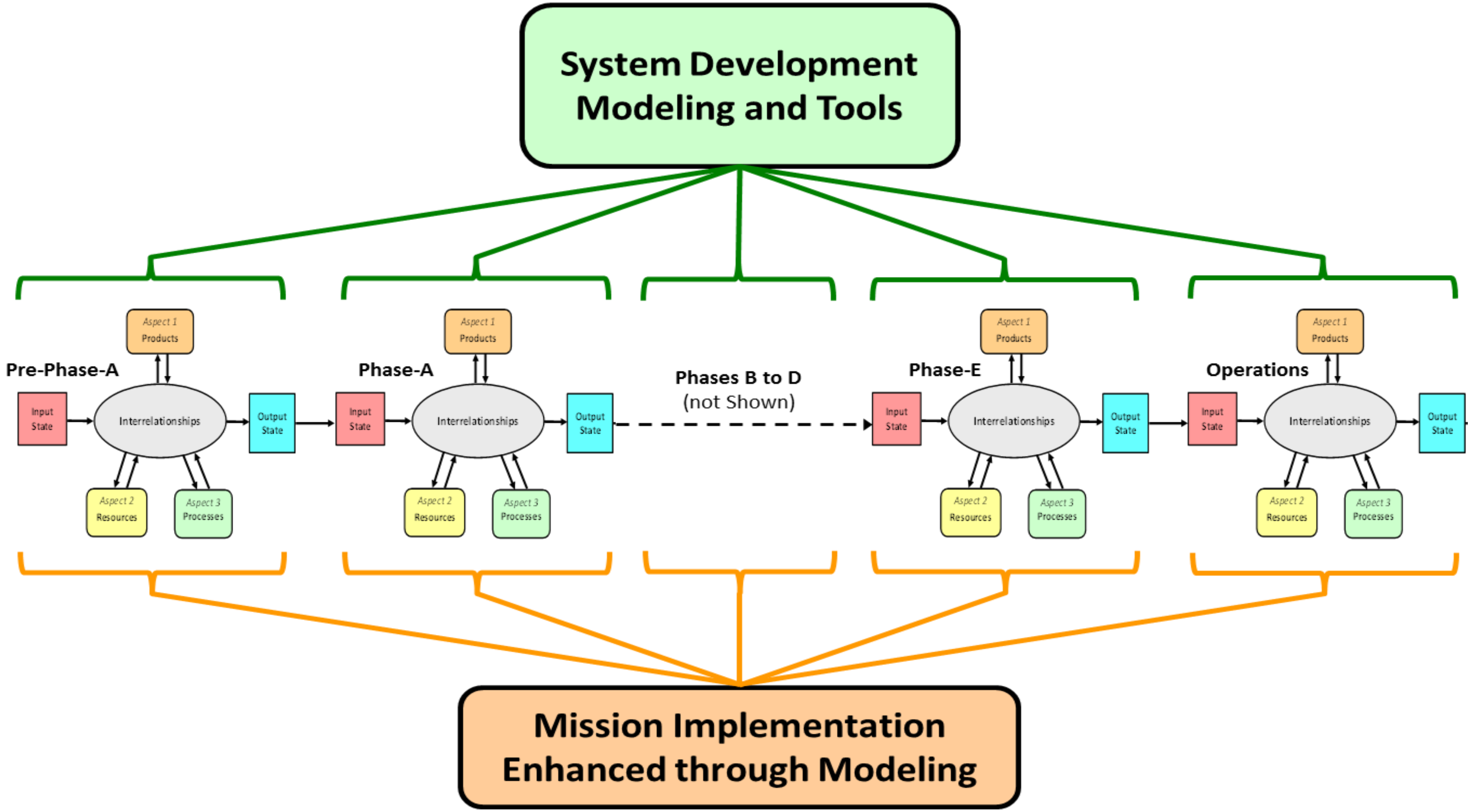
MDL CATTENS Development Tool (FY16-FY17 IRAD)

MDL Study Process (FY17 IRAD)

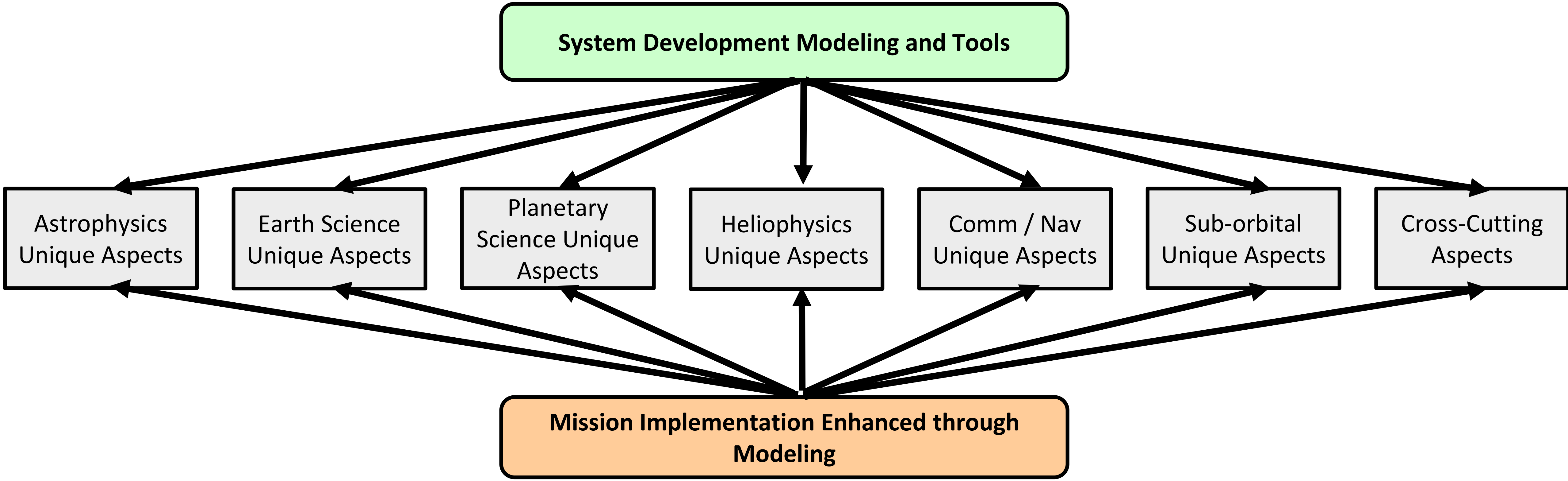
# System Development Process Modeling Vision: All Development & Operation Aspects



# System Development Process Modeling Vision All Life Cycle Phases



# System Development Process Modeling Vision: All GSFC Lines of Business



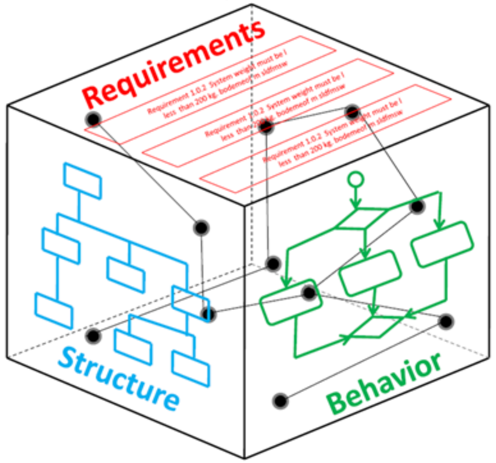

*Specific missions benefit from growing model repository*

# System Development Process: Investment Focus

- Facilitation
- System Development Process
- Discipline Engineers
- Pre-work
- Information Management (PRIME/CATTENS)

MDL Activity (Study)

Analysis Software




Electronic System Model

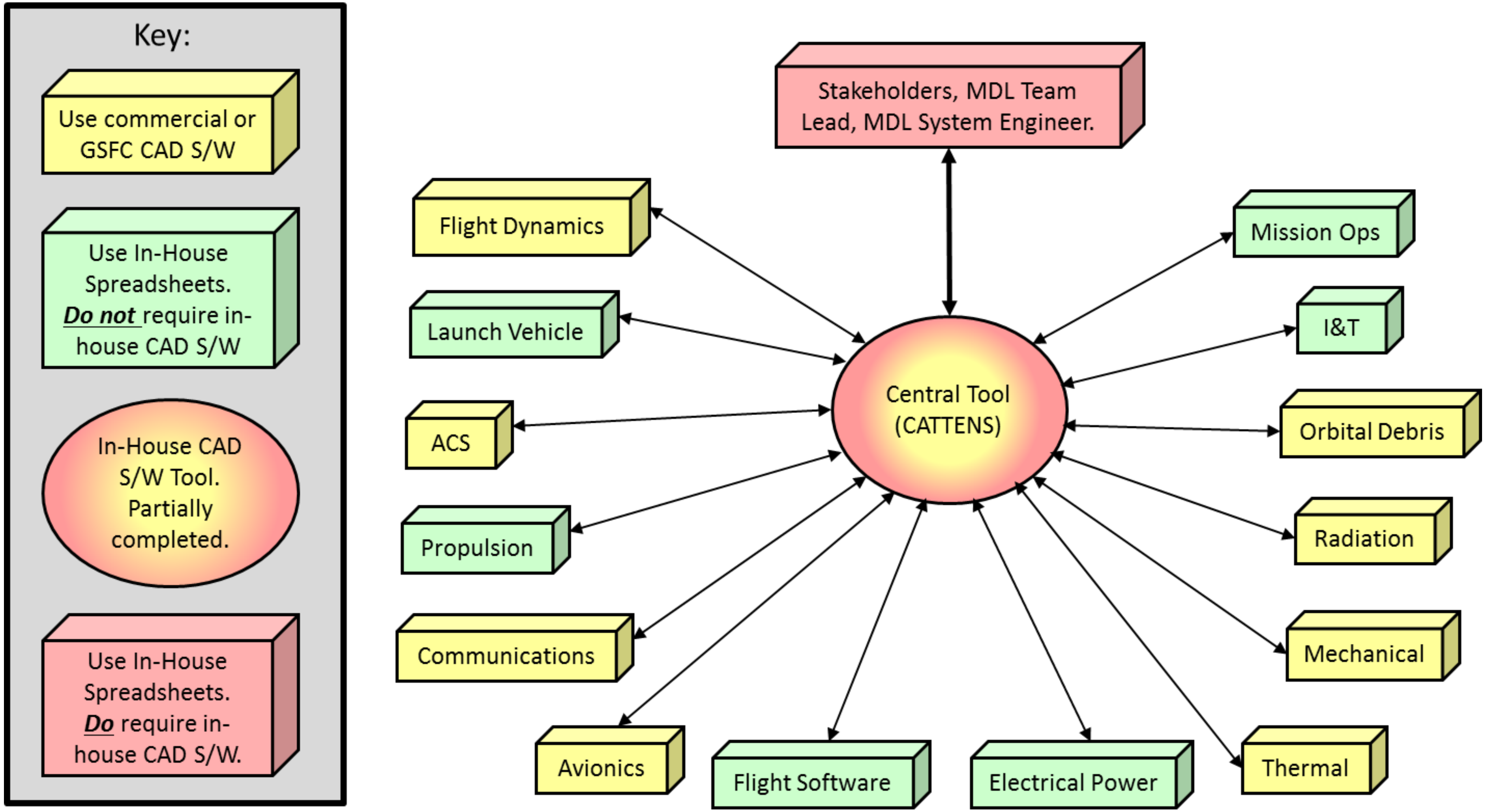
- Science traceability matrix
- Project Need/Goal/Objective
- MEL
- Product Breakdown Structure
- Concept of Operations
- I&T Flow
- …

Documented "System Model"

Focus on the IDC

- Enables support for all GSFC Lines of Business
- Enhanced credibility for proposals
- Enhanced institutional processes provide strong technical and programmatic foundation for Phase A/B

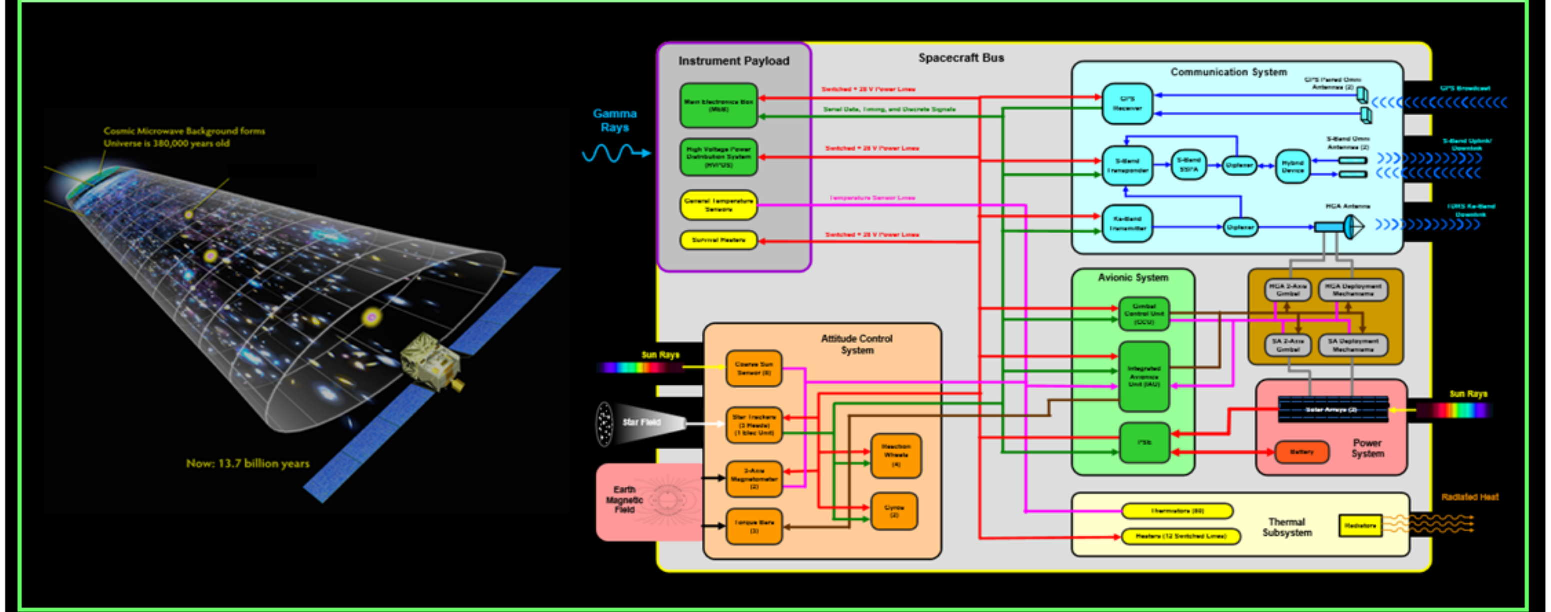
# State of the Art: A systems engineering tool for the MDL



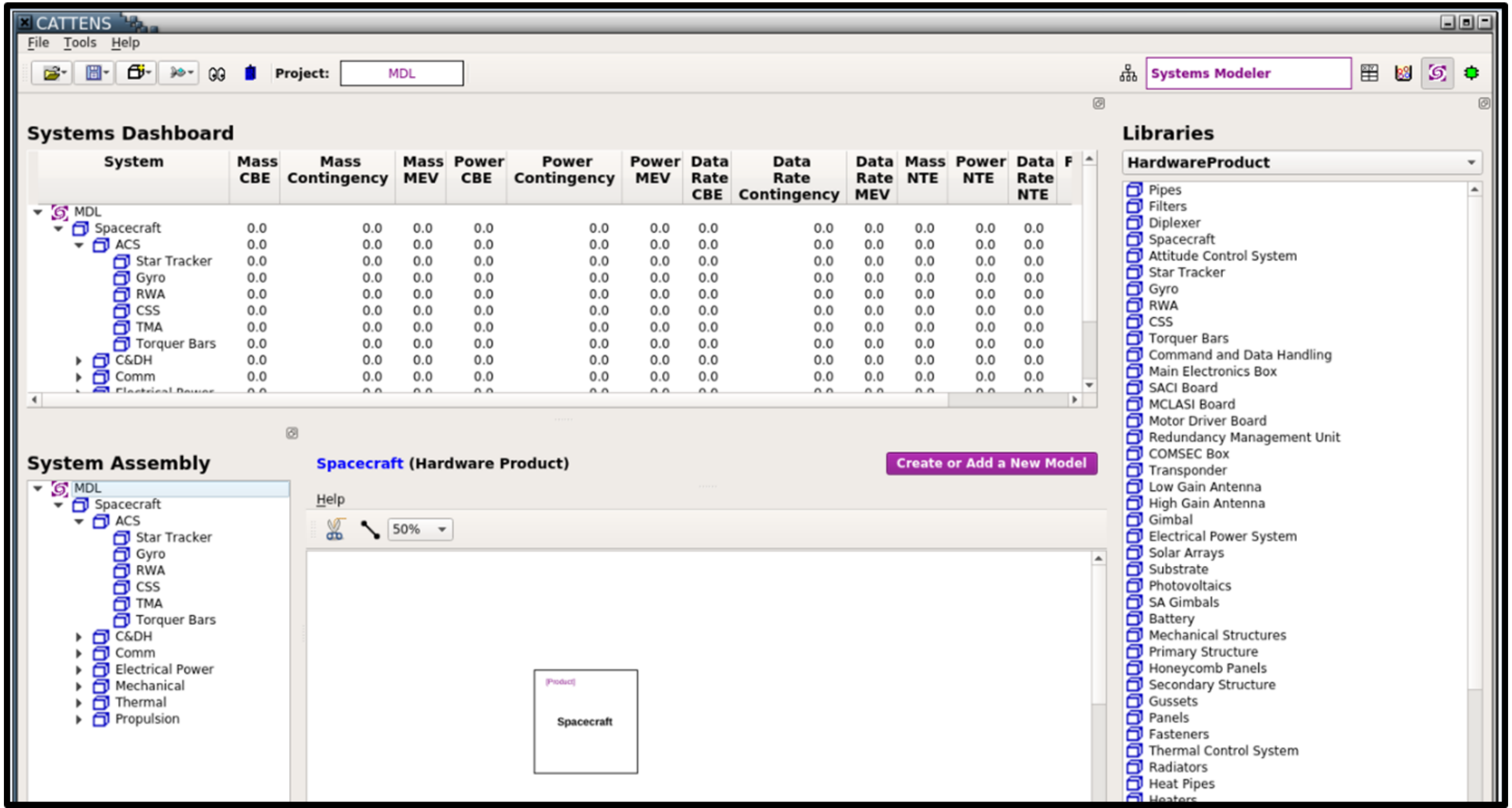
# Vision: A systems engineering tool for the MDL

**Study Aspect Selection Menu**

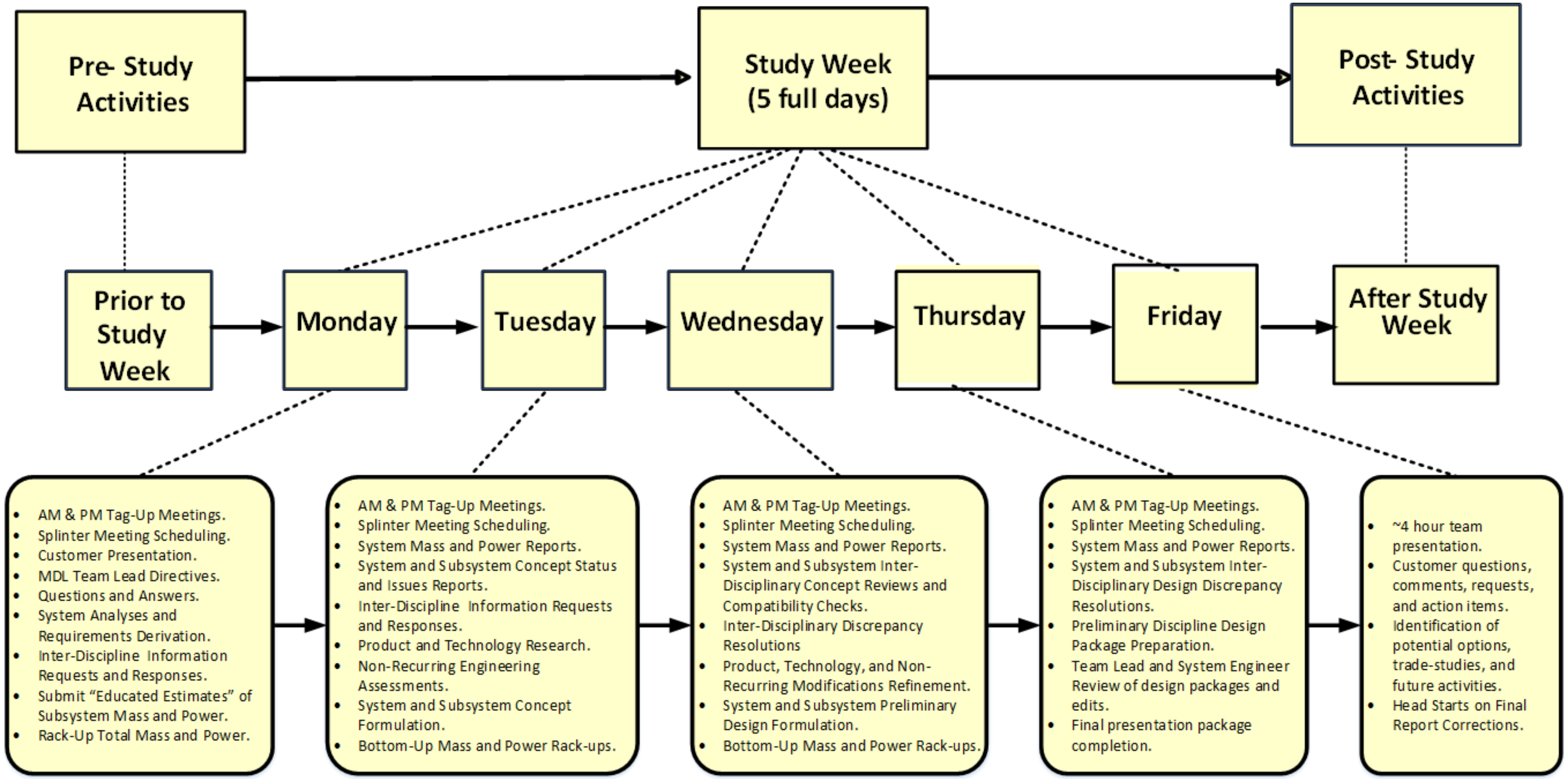
| Study Management | Initial Data | Current Data | |
|---|---|---|---|
| Study Plan and Schedule | Customer/Stakeholder | *Discipline Files* | Component Technical Specs |
| Study and Discipline Status | ADL, MDL, and IDL Studies | *Requirements* | Trade Studies |
| Team List and Attendance | Industry Products & Technologies | *System Analyses* | Requirements Verification Matrix |
| Splinter Meeting Plans | Standard Templates | *Mission Breakdown Structure* | Evaluations, Decisions, & Rationale |
| Team & Discipline Action Items | | *Master Equipment List (MEL)* | |
| Discipline Technical Info Requests | | *Harware and Software Designs* | |



# State of the Art: CATTENS, Product Development



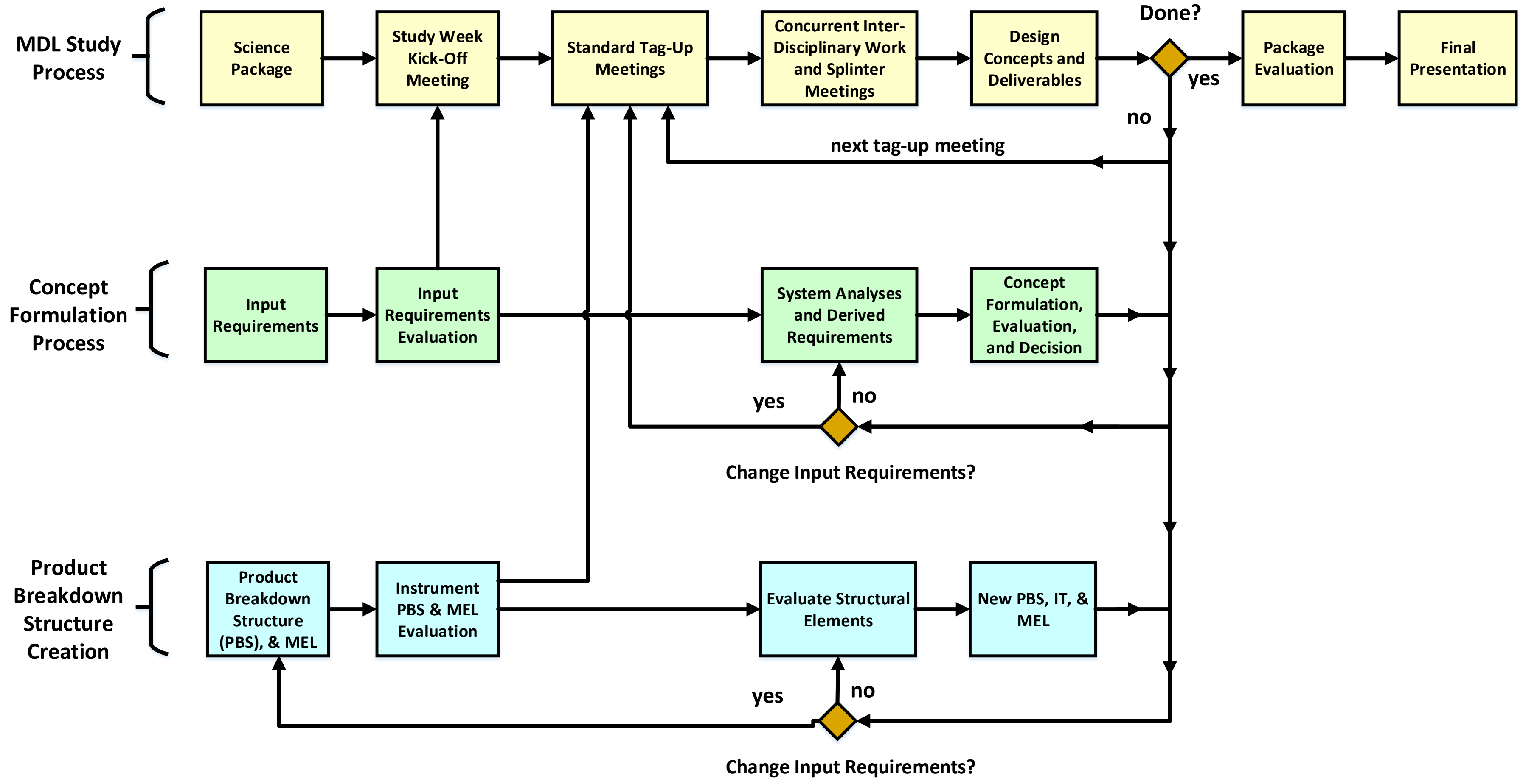
# Systems Engineering: Modeling the MDL




The MDL as we understood it, 2017

- Facilitated Mission Design activity
- Successful History of Mission Capture
- Static report output

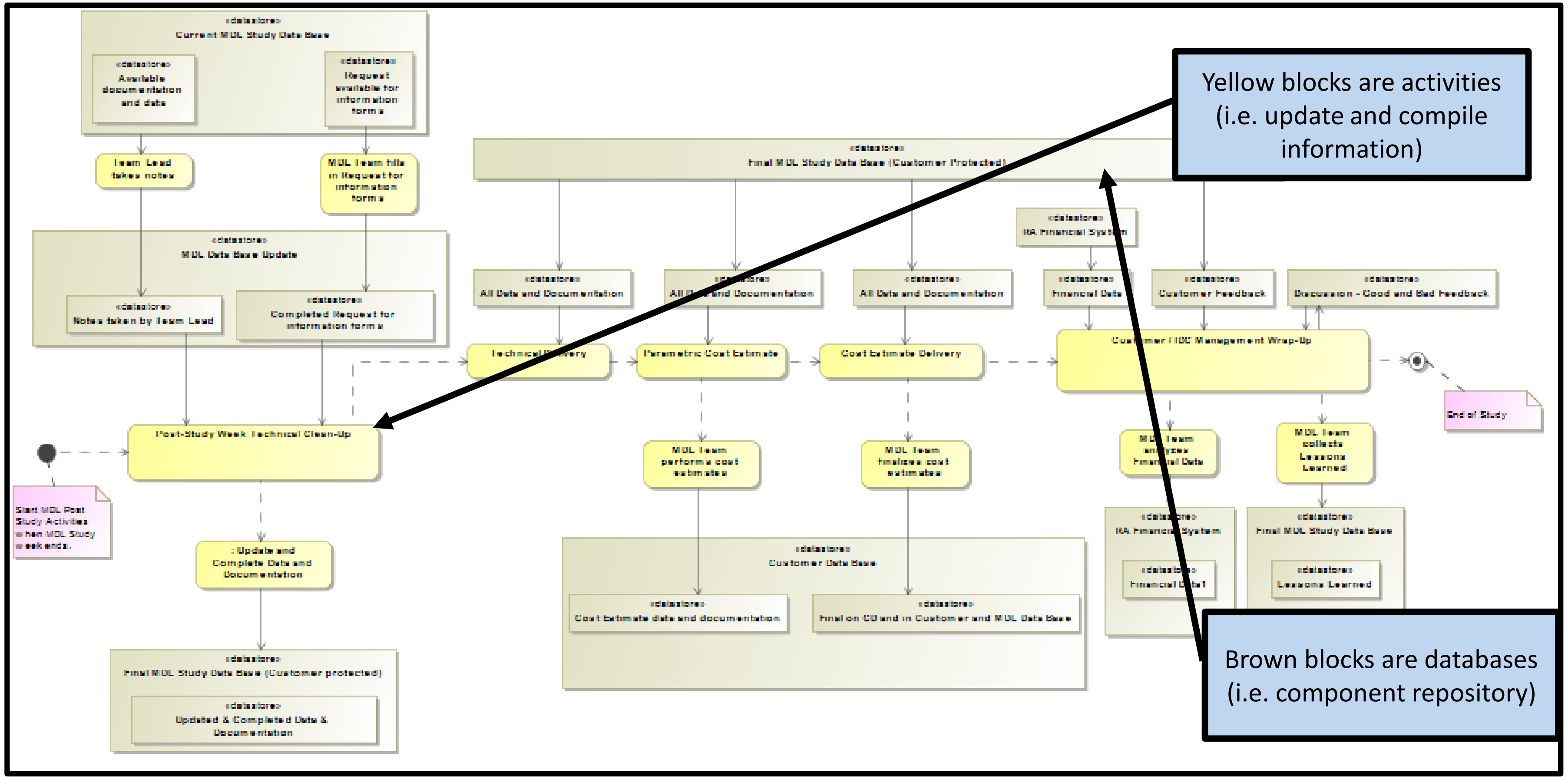
# Systems Engineering: Modeling the MDL




Systems Engineering Products (FY '17)

- Graphical description of structure and behavior, designed with stakeholders
- SE Process from NPR 7123
- Foundation for SysML model of MDL

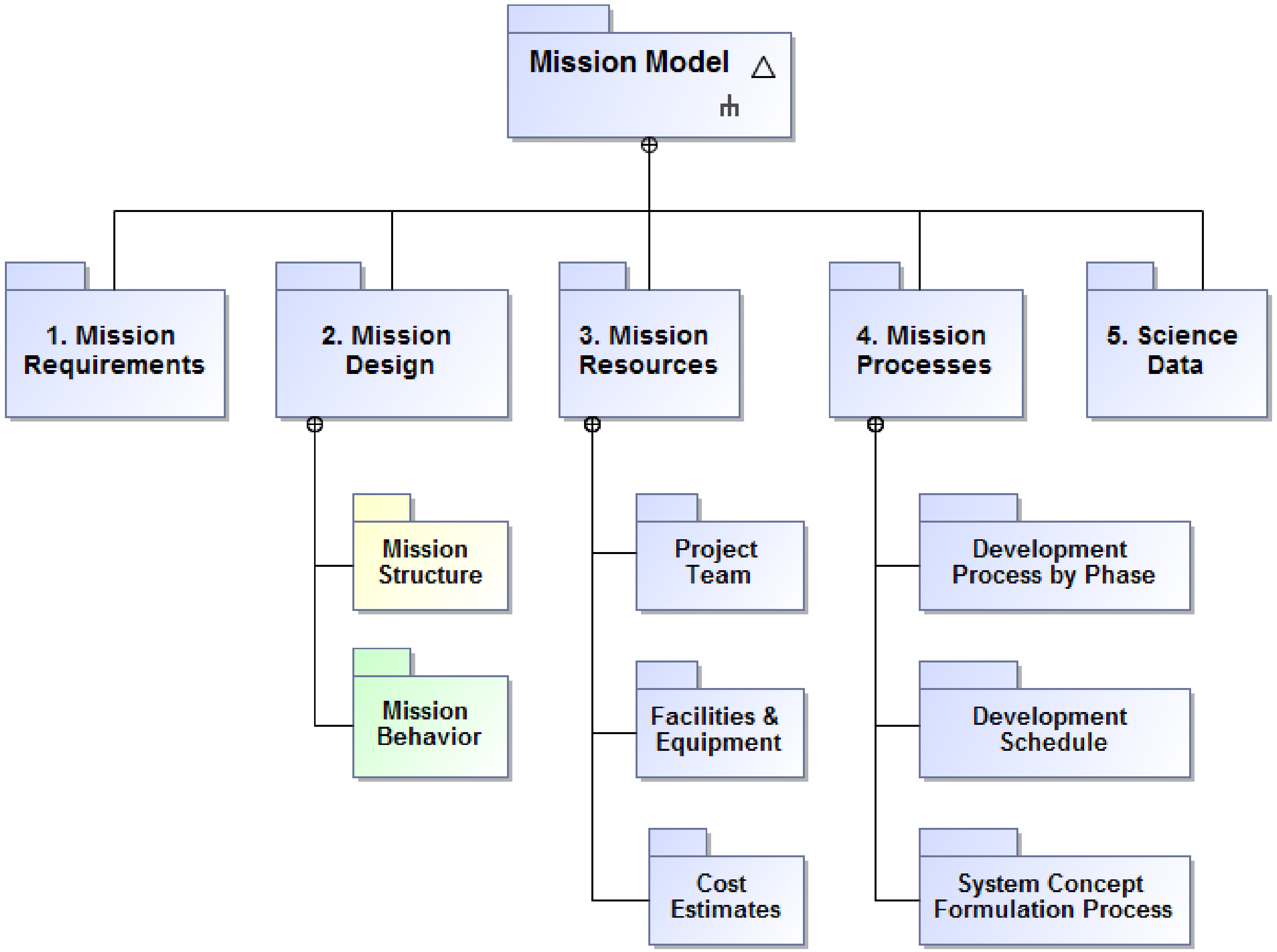
# Systems Engineering: Modeling the MDL




The MDL as we understand it, 2018

- Rigorous and clear description of MDL [SysML model]
- Clearly defined specifications [ex: pre-work, database information]
- Guides and specifies CATTENS and future SE Software development

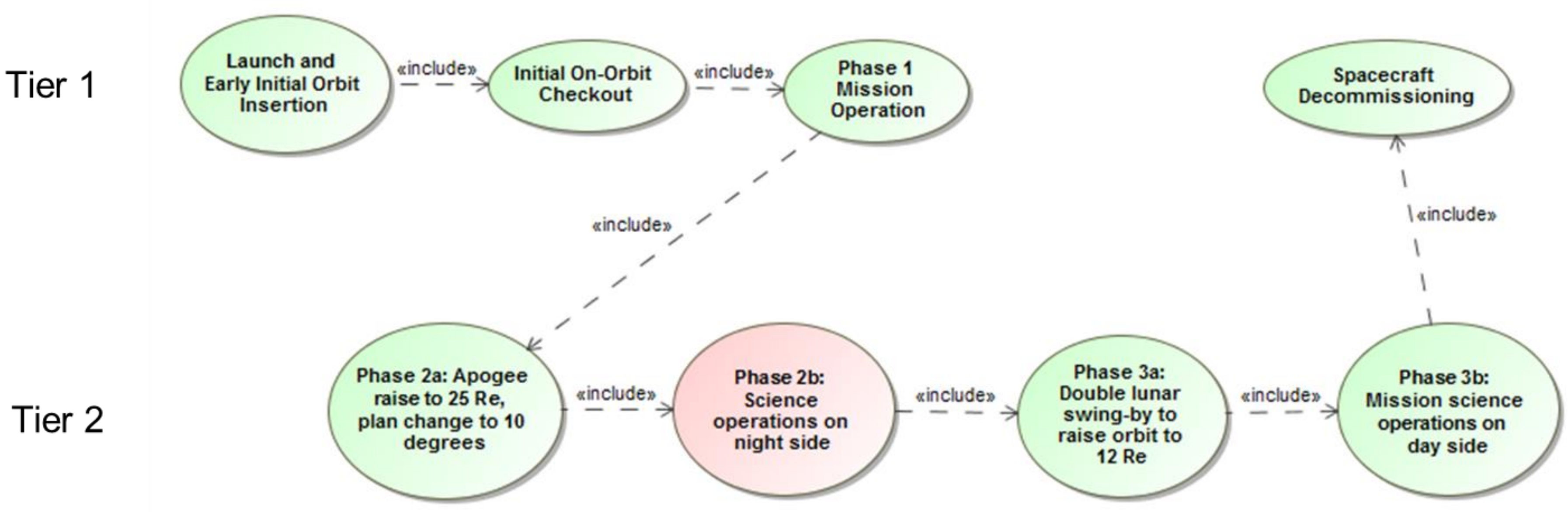
# Systems Engineering: The Mission Model




In 2018 we will create a SysML model of the MMS mission

- Pathfinder activity
- Guides and specifies CATTENS and MDL output
- Facilitates the use of SysML models
  - Design
  - Analysis
  - Communication

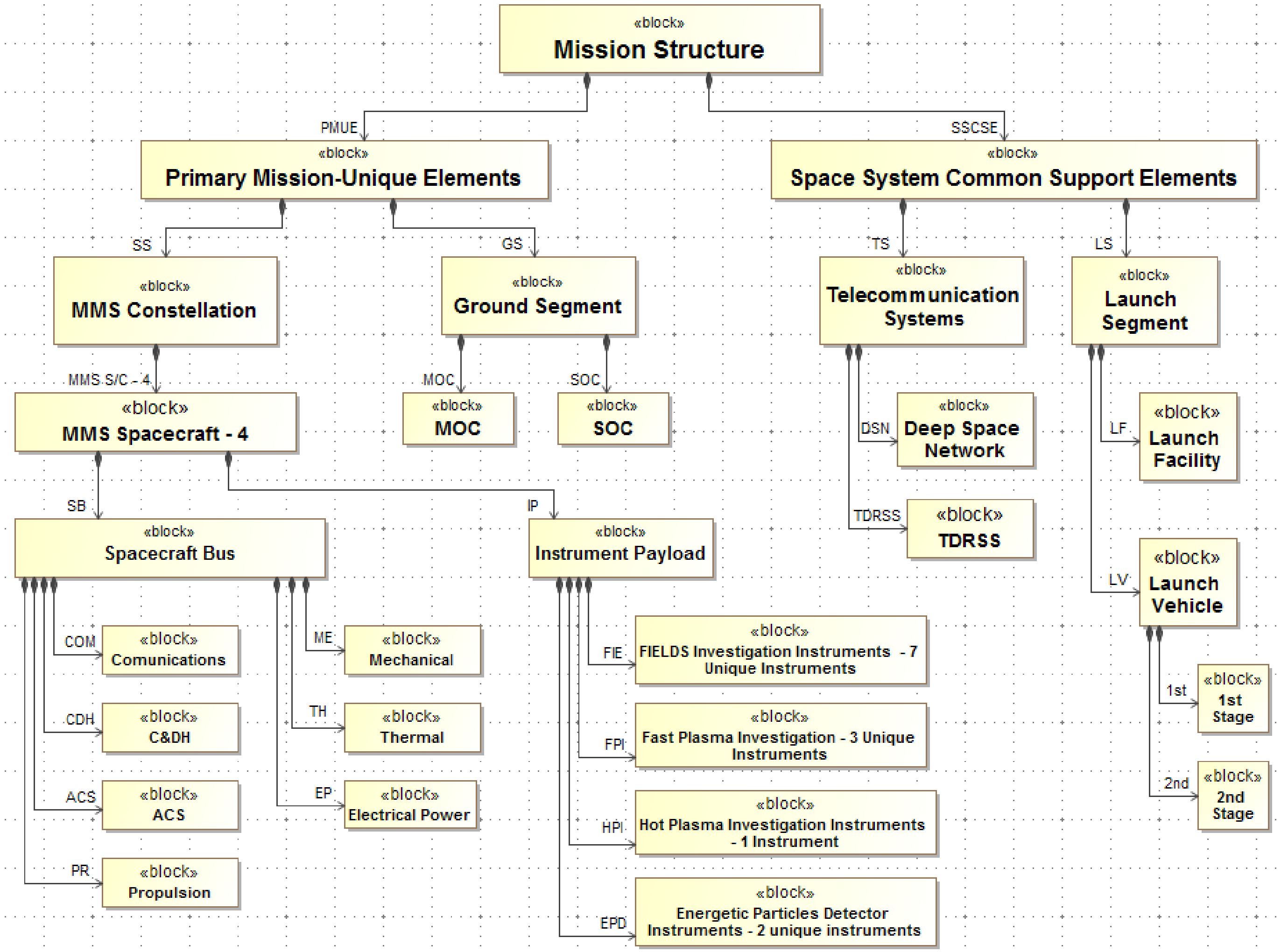
# Systems Engineering: The Mission Model




MMS Mission Model

- Behavioral element of the Architecture
- Clearly defined
- Structure, behavior and requirements linked

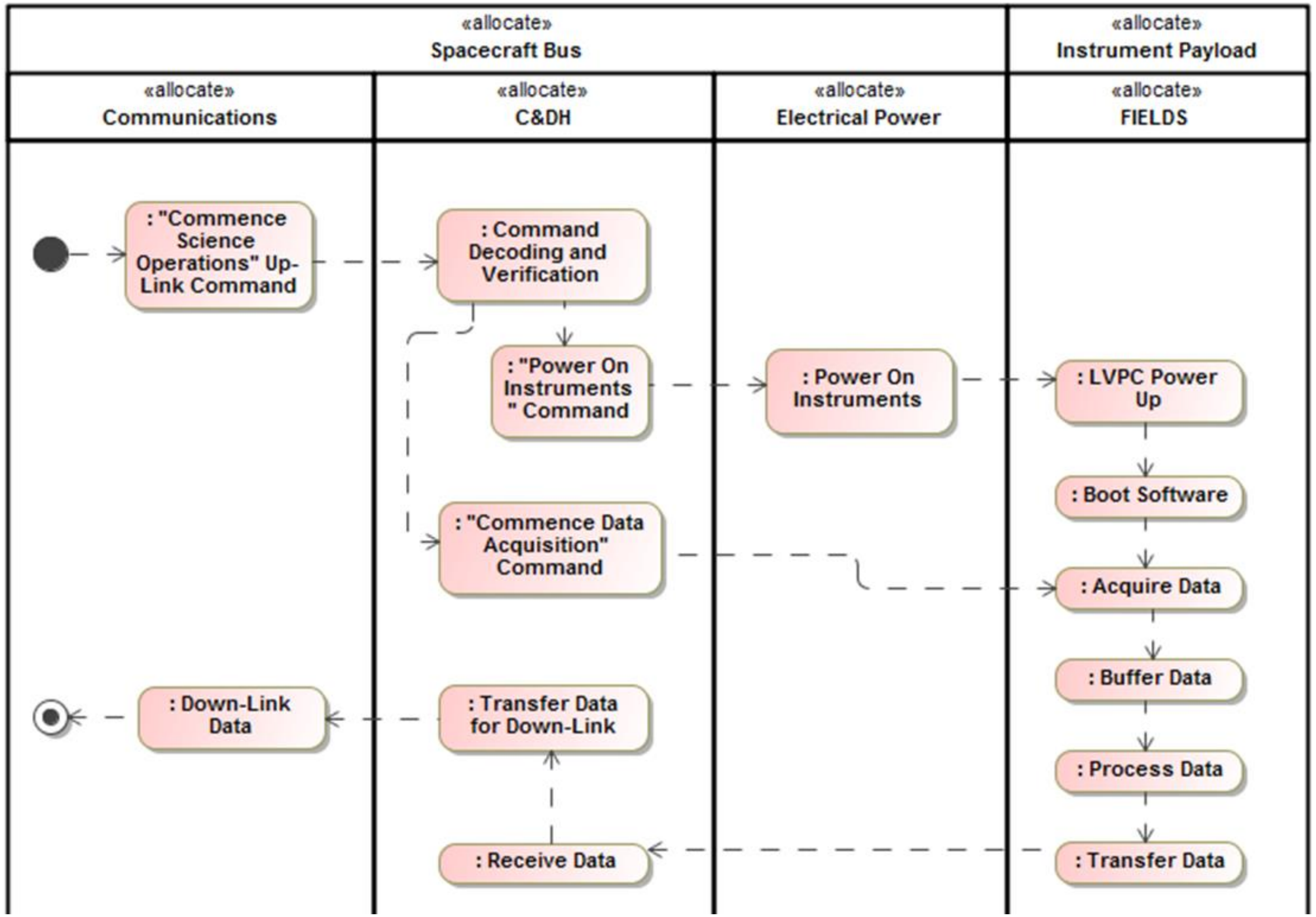
# Systems Engineering: The Mission Model




MMS Mission Model

- This diagram is the structural element of the Architecture
- Clearly defined
- Structure, behavior and requirements linked

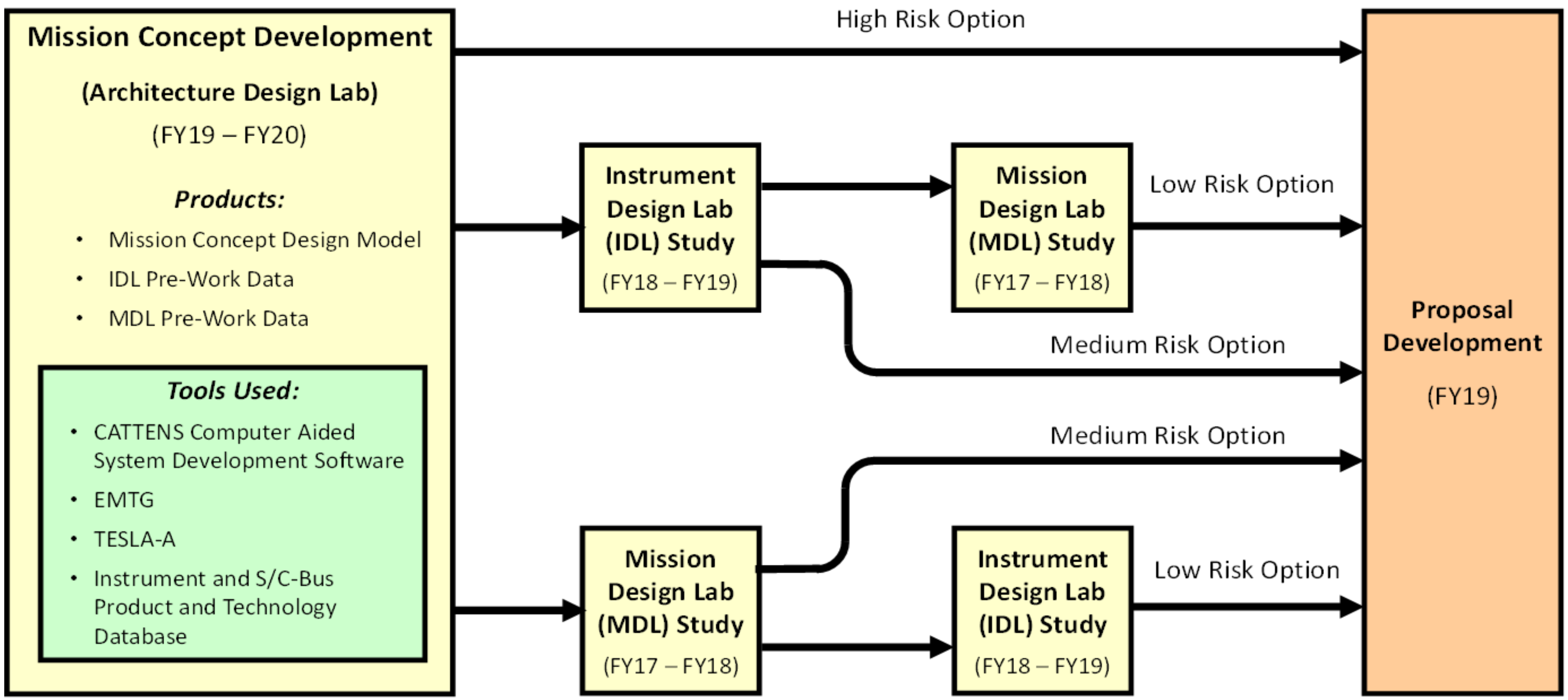
# Systems Engineering: The Mission Model




MMS Mission Model

- Data model
- Clearly defined
- Structure, behavior and requirements linked

# Vision: An Integrated Modeling Environment




Mission Architecture

- Begins in ADL, creating foundation model
- IDL and MDL activities integrate into model
- Resultant model is in place to support:
  - Risk management model
  - EVM model
  - Workforce planning model

# Recap: MBSE offers process improvement throughout the SE cradle-to-grave cycle

**Process efficiencies:**
**Reduced effort, time and cost in executing SE processes**

- Automatic generation of documents, briefing materials, etc.
- Improved support for program reviews, decision milestones, etc.
- Improved reuse of known-good designs and exiting architectural elements
- Ready availability of information on system baselines
- Clearly articulated concepts
- More rapid communication within team
- Faster convergence on multi-discipline / multi-organizational problems

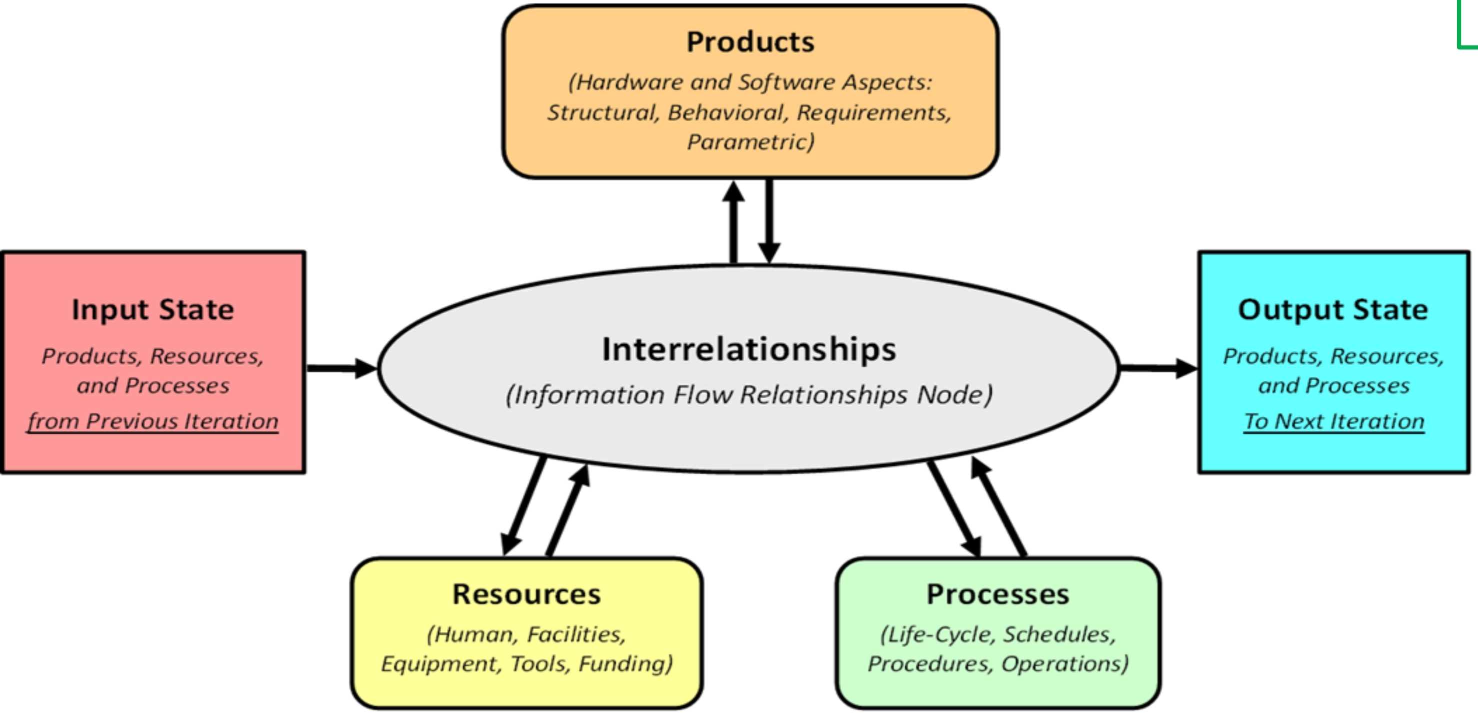
**Enhanced quality and integrity in system architectures**

- Improved and earlier detection of design errors, wrong or missing requirements, conflicting interface definitions, etc.
- Improved communication and shared understanding among disciplines, teams, and stakeholders
- Improved tools for requirements analysis, allocation, and tracing
- Payoffs from Object-Orientation - Abstraction/Inheritance, Modularity, Loose Coupling, Interface Management, and others
- Framework for modeling and simulation at multiple levels

# MBSE Activities at GSFC

Sounding Rocket Design (FY16-FY18 Pathfinder)

MMS and DSM Mission Design (FY18 IRAD)




Origins Space Telescope
(FY18, Astro Decadal Study) (Pre-A)

WFIRST Integrated Modeling
(FY18, Astro Flagship, A)

MEME-X
(FY18, Helio Explorer Study, A)

Instrument Development Laboratory
(FY18, IDC Study)

Europa Lander
(FY18, Planetary, Pre-A)

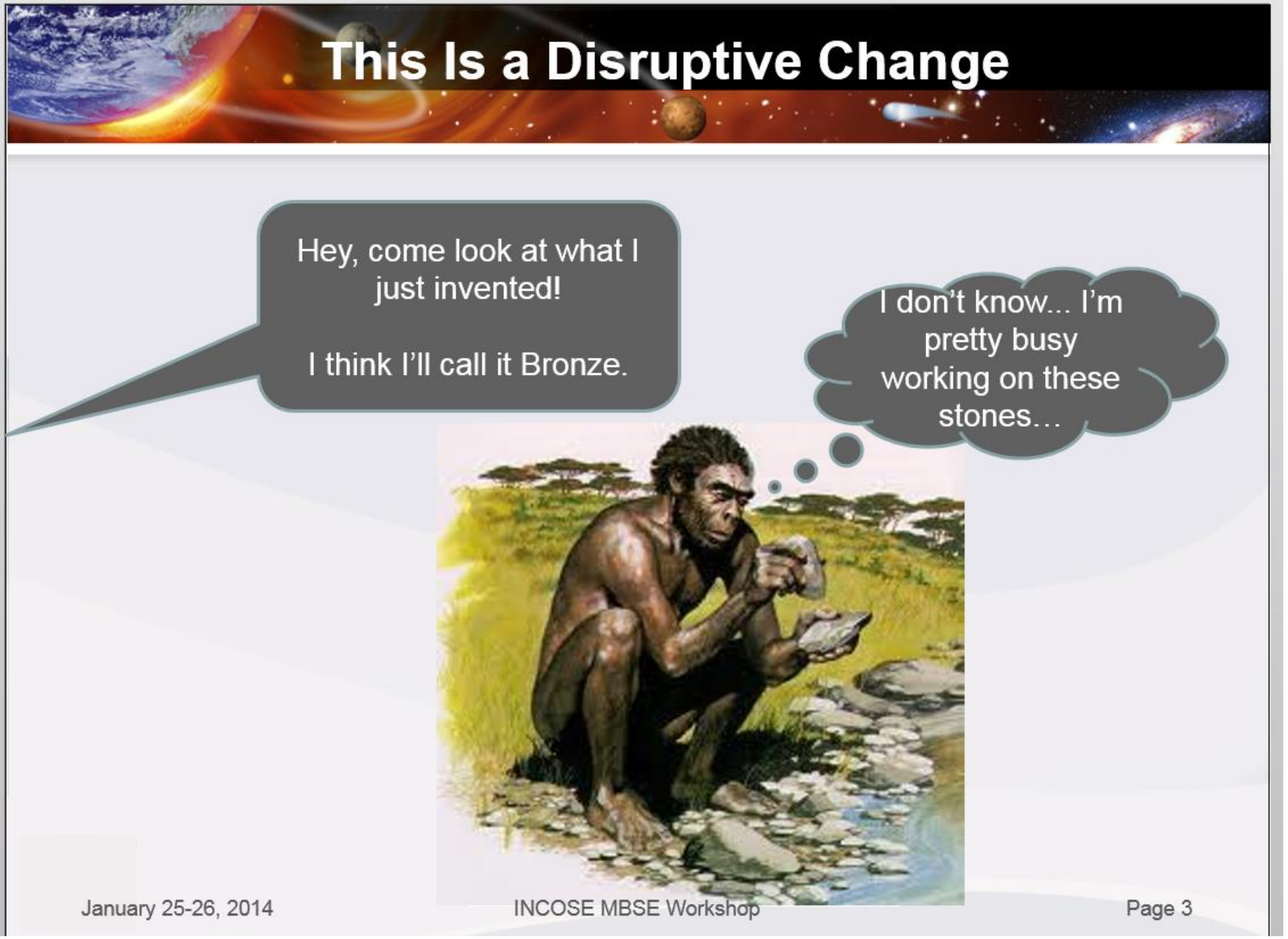
Future Efforts

Sounding Rocket Development Process (FY16-FY18 Pathfinder)

MDL CATTENS Development Tool (FY16-FY17 IRAD)

MDL Study Process (FY17 IRAD)

# MBSE: A few comments on change and culture

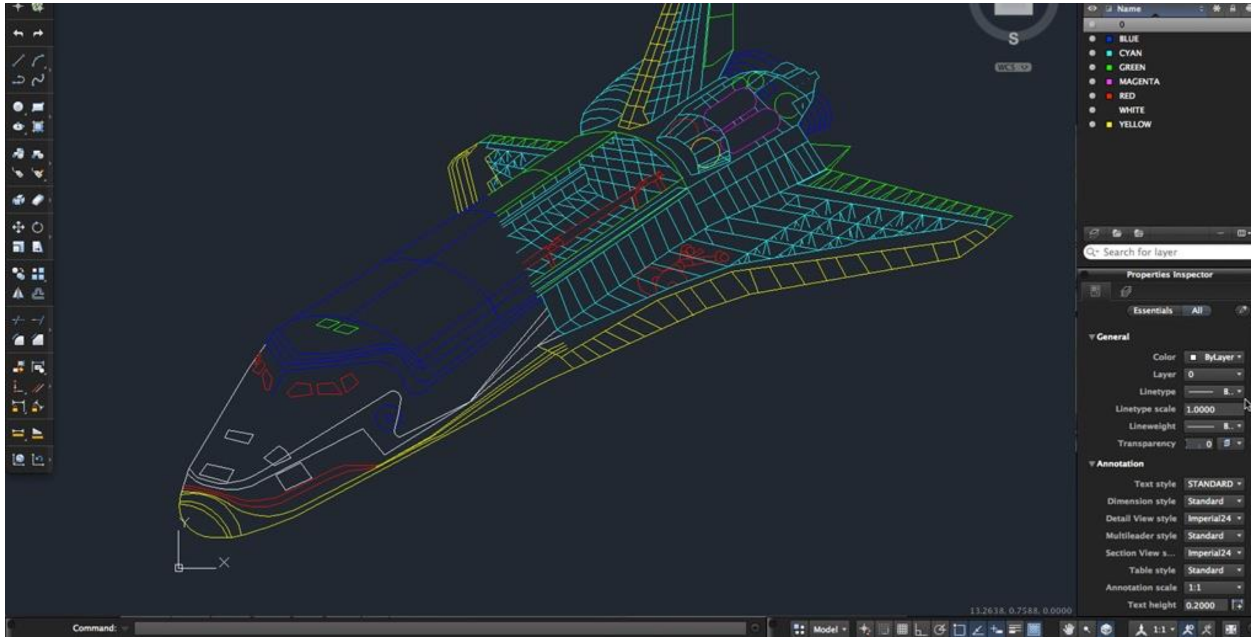



Lessons learned at NASA, specifically JPL, an early adopter and leader of MBSE

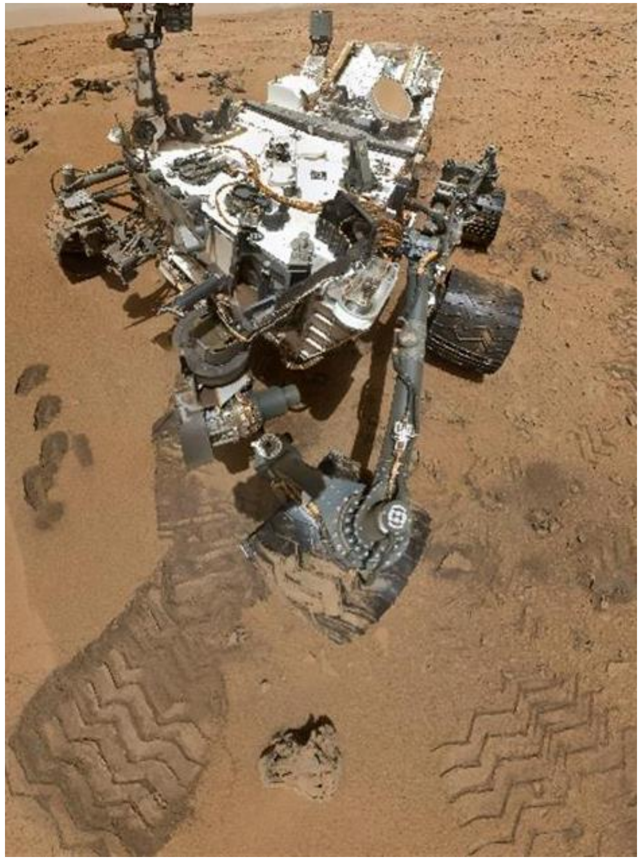
- Disruptive innovation – not really a software change, rather a change in the **approach** to Systems Engineering and **activities**
- **Academically understood benefit** – challenge to **balance** development vs. deliverable
- Barriers to change are real, even when improvement is a goal
  - Vocabulary
  - Quality Assessment
  - Transferability
  - Stakeholder Assessment

# The Model Based Approach “Value Proposition”


Disruptive innovation



# The Model Based Approach “Value Proposition”



Innovation->Enabling technology

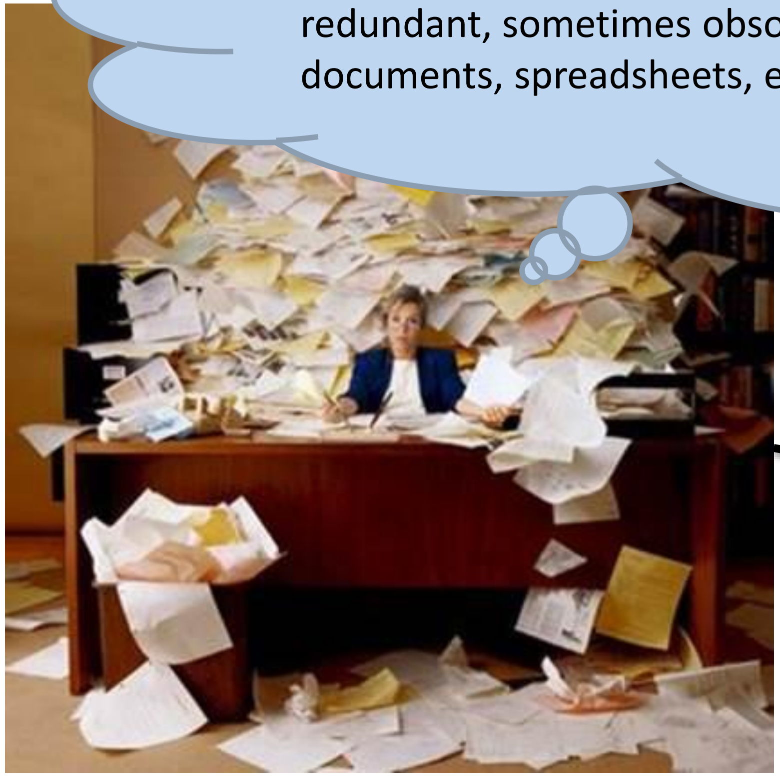
NASA releases free 3D printable files for Curiosity Mars Rover

3D printing is an element of the Mars exploration architectures

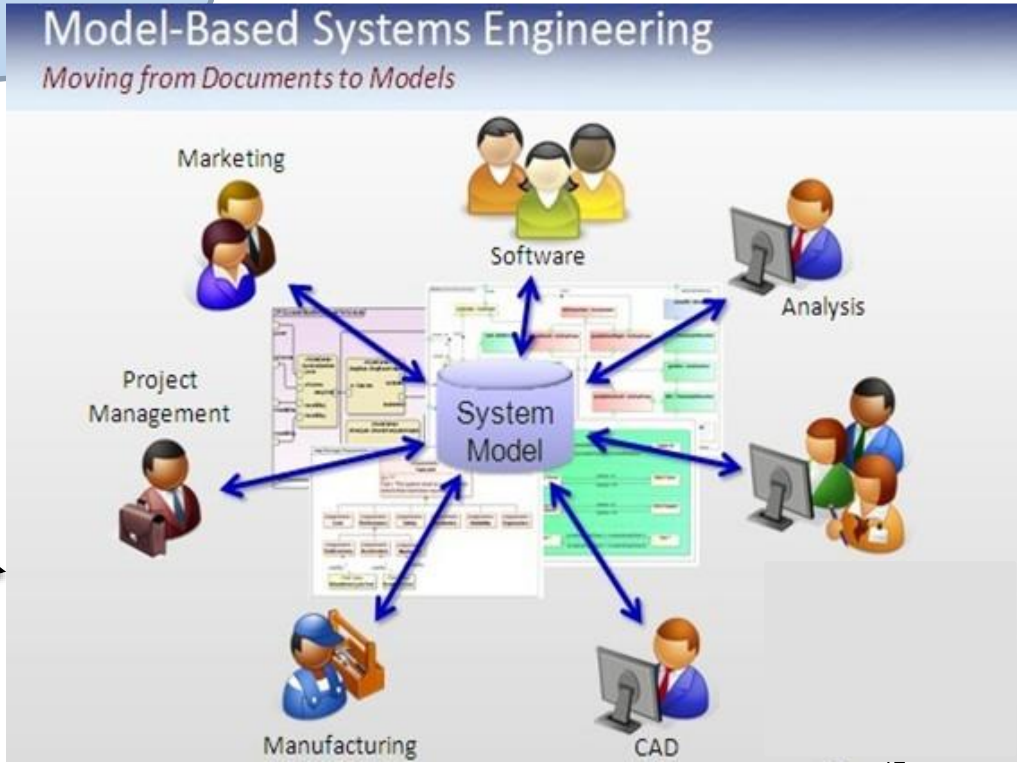
CAD enables Martian Exploration!

## System Model (Flight & Ground Systems): The collection of abstractions, assumptions, and descriptions of physical components and processes representing the reality of interest

Reduce the amount of effort required of the analysts to harvest oodles of information: A multitude of sometimes redundant, sometimes obsolete, oftentimes out-of-sync documents, spreadsheets, e-mails or whatever…

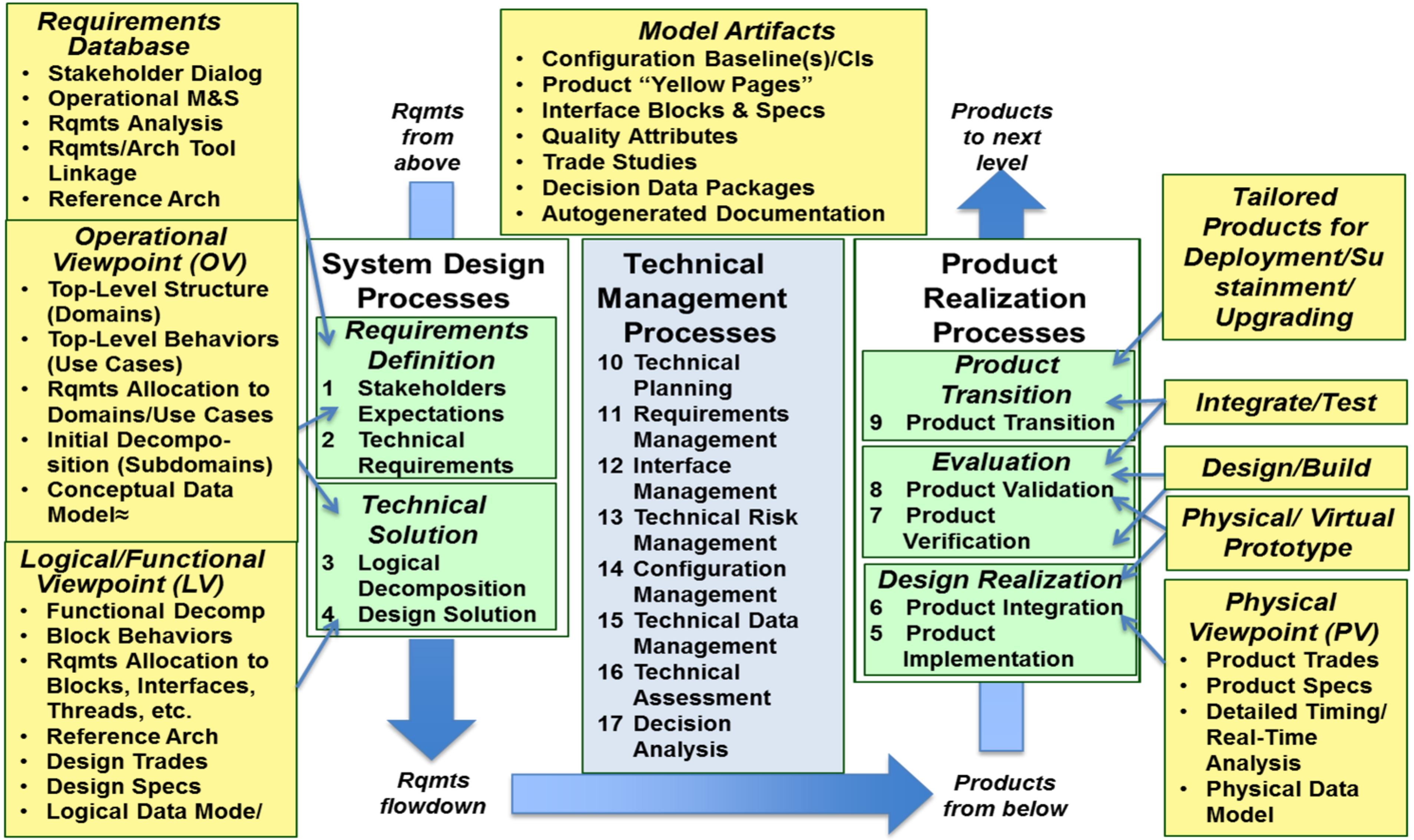


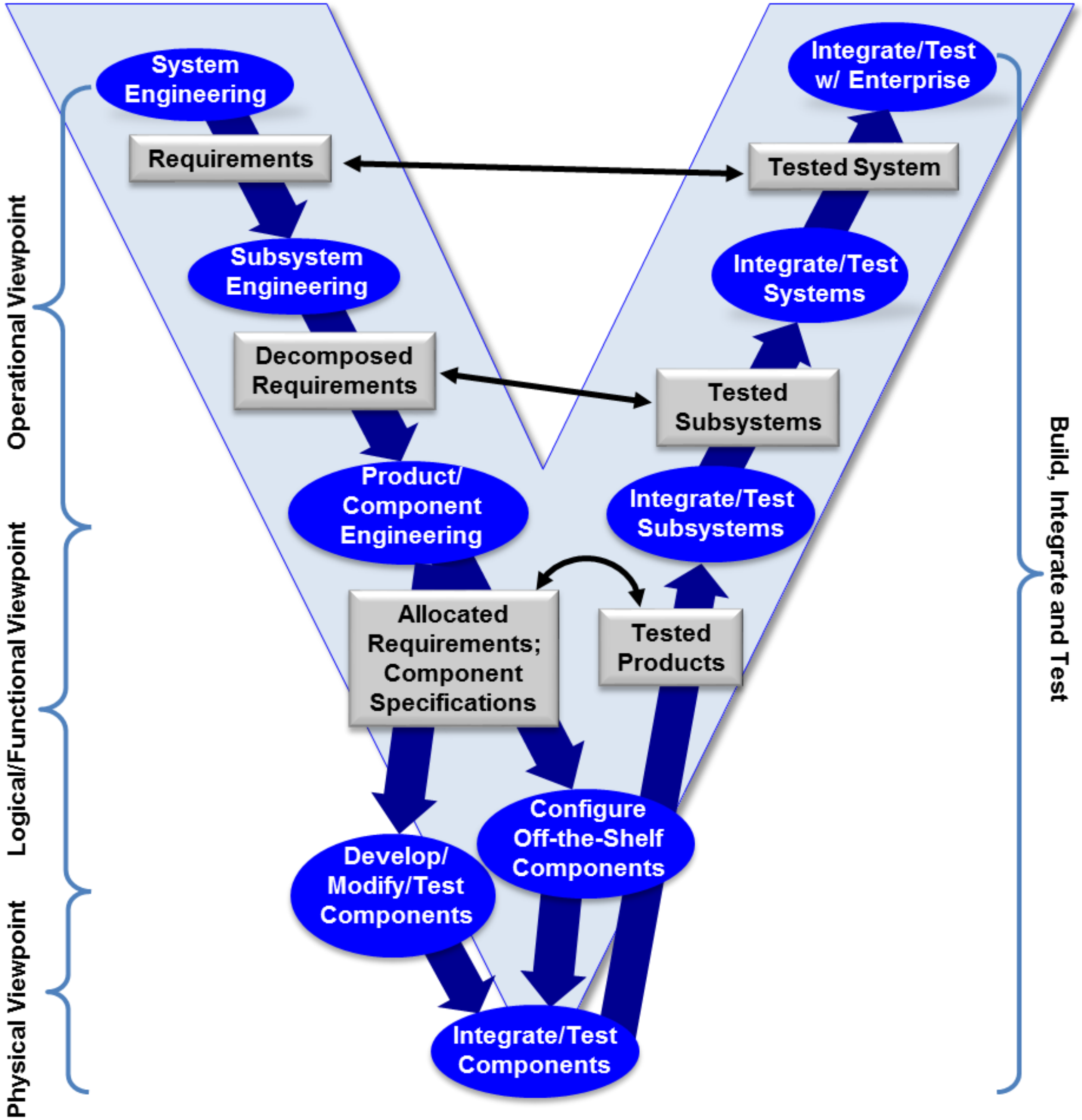
Disruptive innovation



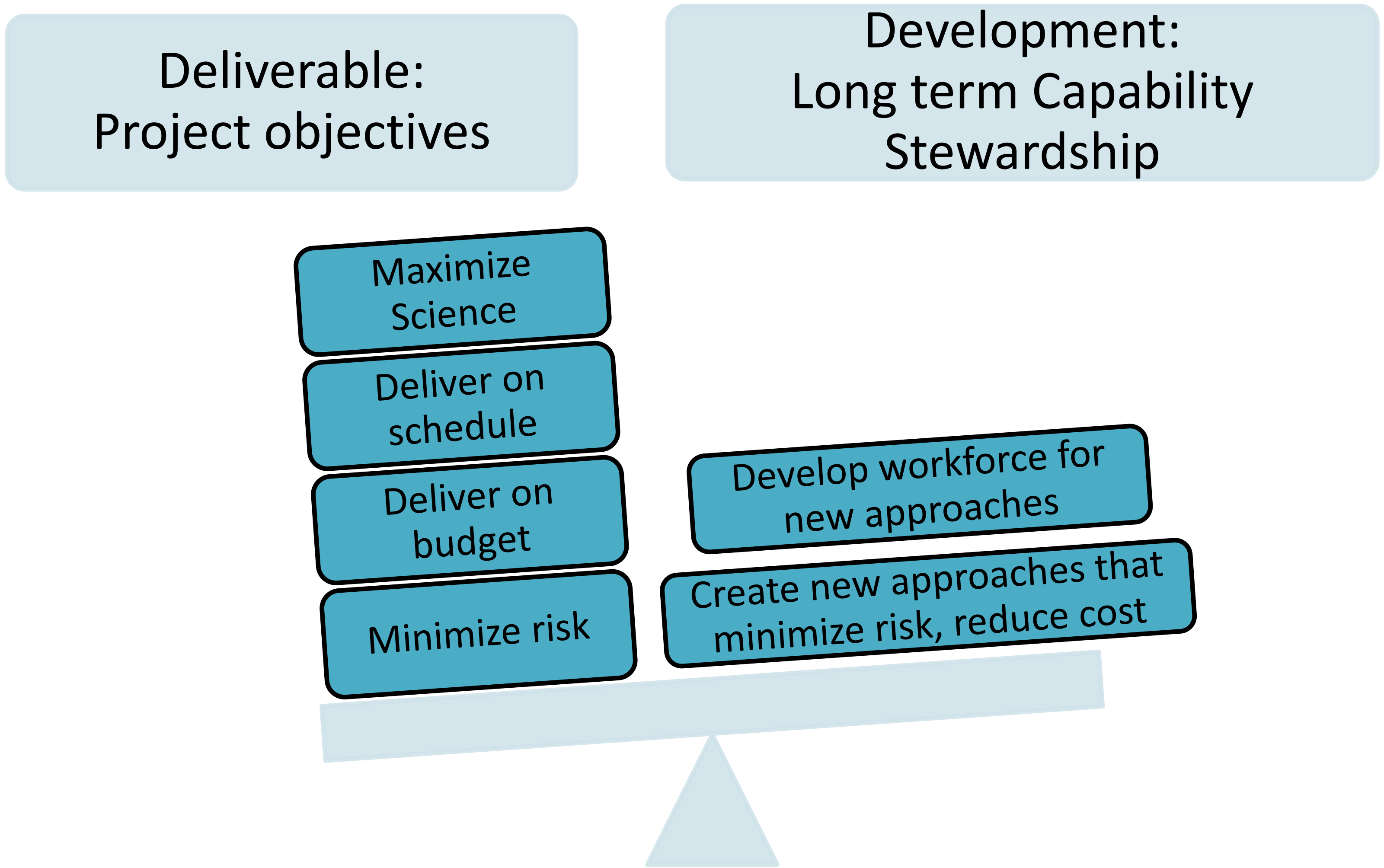
# Model Based Systems Engineering

*Model Based Systems Engineering Strategy*




System Engineering
Requirements
Subsystem Engineering
Decomposed Requirements
Product/ Component Engineering
Allocated Requirements; Component Specifications
Develop/ Modify/Test Components
Configure Off-the-Shelf Components
Integrate/Test Components
Tested Products
Integrate/Test Subsystems
Tested Subsystems
Integrate/Test Systems
Tested System
Integrate/Test w/ Enterprise
Operational Viewpoint
Logical/Functional Viewpoint
Physical Viewpoint
Build, Integrate and Test

**Q1: What are the major bottlenecks for a comprehensive model based systems engineering capability?**
**A1: Potential for disconnects that independent organizational objectives can present in matrixed organizations.**



**Q2: What approach do you advocate to move MBSE forward in industry, government and academia?**

**A2: High level policy, with a deliberate hand in policy flow down, coupled with grass-roots technical activities can ensure strategic intent is realized.**

Agency Policy: Digital methods as a means to better implementation

Program commitment to invest

Long term program benefits

Project Policy: Digital methods are standards, and costs are baseline

Project commitment to participate in transformation

Business as usual technically

Engineering Policy: Digital methods are standard practice, manage the transition responsibly and transparently with Program

Program support work plans are designed for no programmatic impact

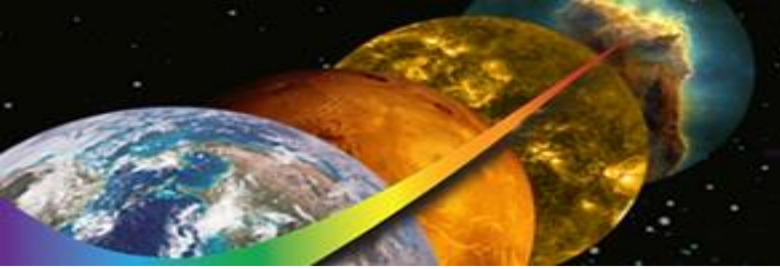
Technical implementation are responsible and transparent, invest in current and future workforce and tools with a balance between development and deliverable.

Inform

Coordinate & Ensure

Perform & Manage

Grass roots technical activities

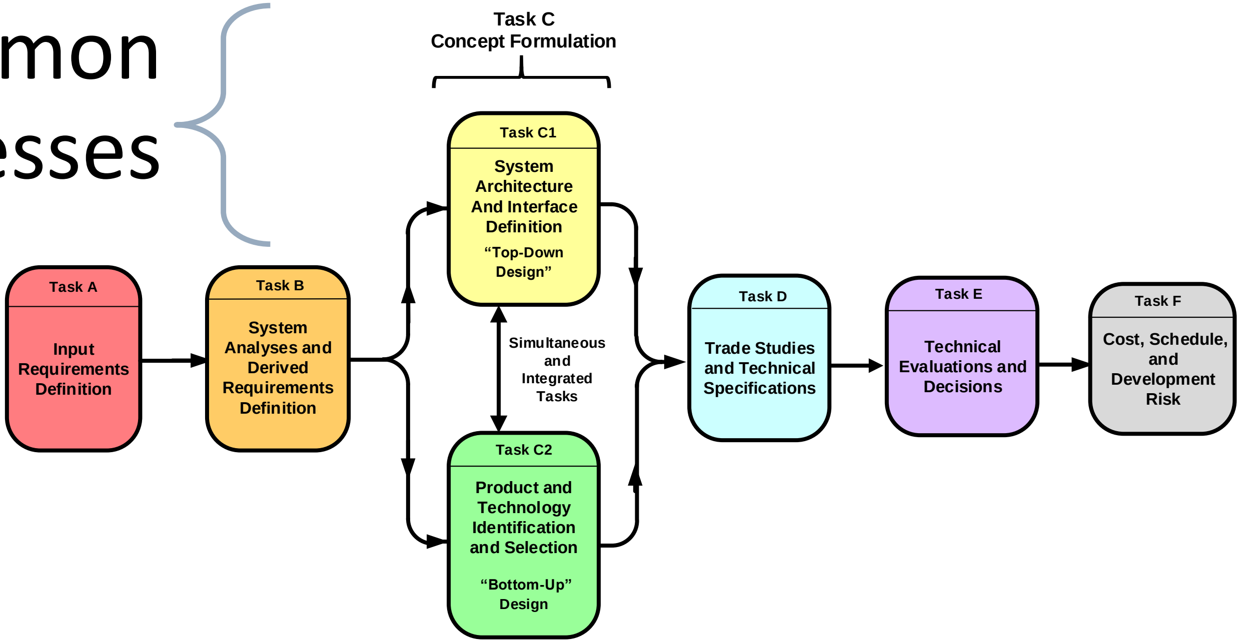




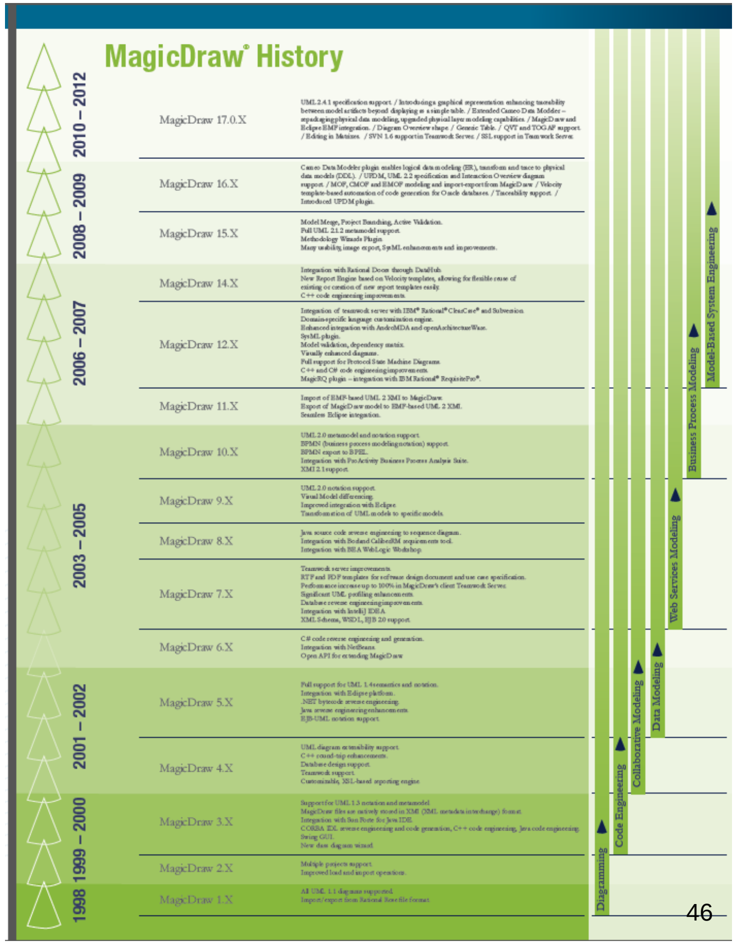
**Q3: What are the next steps and the time horizon for this SE transformation?**

**A3: Coordination across larger entities [communities such as this forum], resulting in standard approaches, tailoring/customization of processes within specific entities, and a call for tools to respond to common needs.**

Common Processes




Industry response to community need



# Summary

- Systems Engineering is challenged like never before (complexity, collaboration, risk posture, cost caps)
- Model Based Systems Engineering offers a viable path forward to improving effectiveness of SE in the current environment
- SysML modeling can provide rigorous and clear management of systems, although other software environments will need to interact with them to make them widely usable: ***Systems Engineering as a Capability, can improve through modeling***
- Change must be ***deliberate***
- If you are even curious about how model based methods can help your project, get in touch with me!

# Questions?