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

David Richardson
NASA-Goddard Space Flight Center
Systems Engineering Forum
Government Transformation to Digital Engineering
May 2, 2018

Model Based Systems Engineering

James Clerk Maxwell

- A Scottish scientist in the field of mathematical physics
- June 13, 1831 – November 5, 1879
- 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.

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

p_i = Probability of occurring in state i

Entropy is often equated to disorder or uncertainty

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”

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

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.

Agenda

- Overview
- A Case for Change [To the Community]
- A Case for the Same [To the Practitioners]
- An Exercise in Culture Change
- A Vision: Computer Aided Systems Engineering [The Stretch Goal…]
- A Model Based Integrated Design Center [The “Use Case”]

Overview

- Who am I, and what is my role?

- Leadership: "Find the way, point the way, get out of the way…"
  - PG1: (Leadership – Find the Way) **Identify the MBSE approaches that will enhance the Center's ability to identify appropriate mission and instrument designs and improve their implementations which provide better science return within appropriate cost and risk postures.**
  - PG2: (Leadership – Find the Way) Create a "right-sized" MBSE technical capability to support the current mission workload of the Center.
  - PG3: (Leadership – Point the Way) **Educate, demonstrate and pilot MBSE projects that bring the user community into the discussion about MBSE, so they can identify the tangible benefits their program/projects will realize from an MBSE approach.**
  - PG4: (Leadership – Point the Way) Transform projects, by infusing the appropriate MBSE capabilities into them.

- Today's journey: Weigh the MBSE value proposition, articulate **one** potential path forward

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

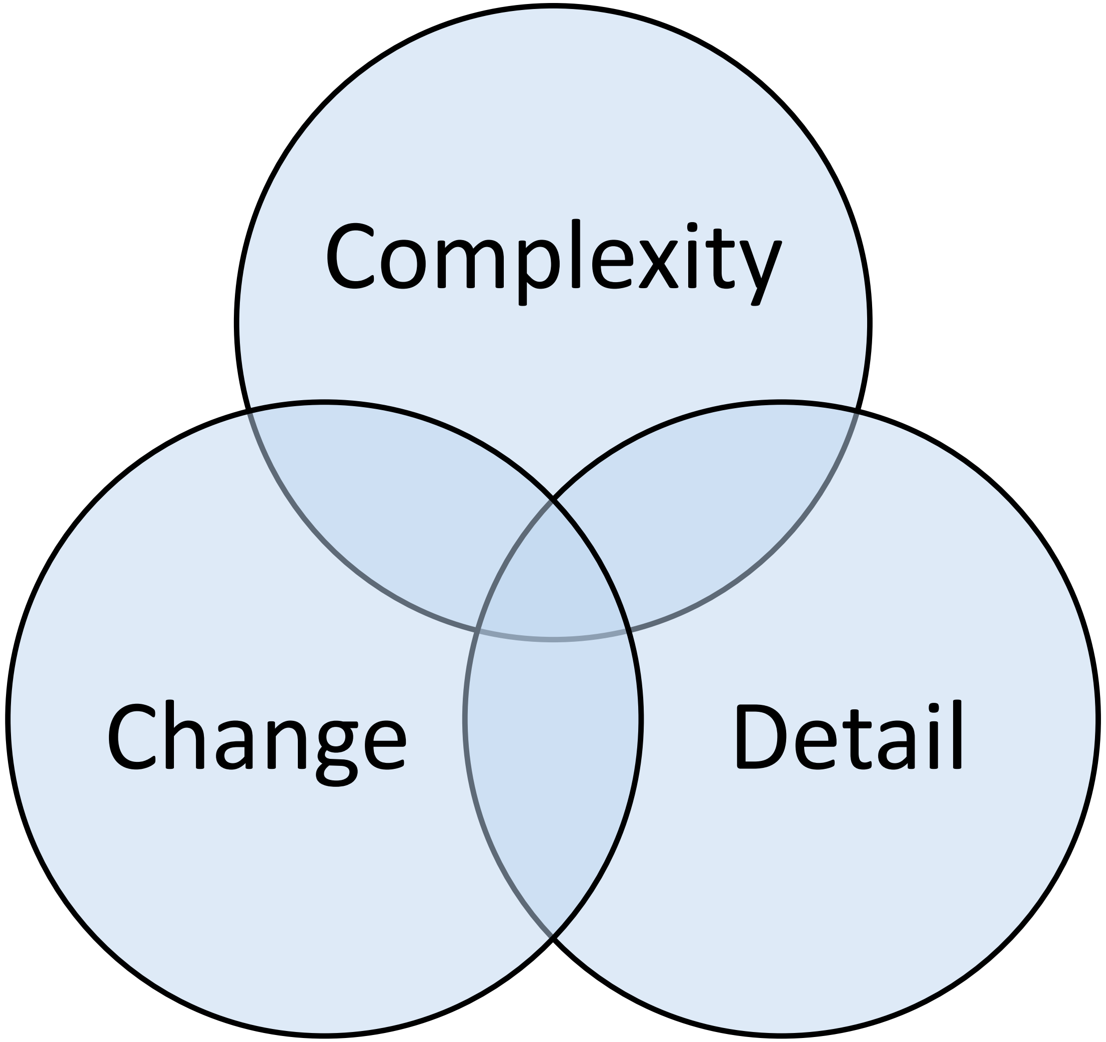
- **Full lifecycle support for NASA missions**
- **Some of the most difficult technical engineering ever**
- **Ambitious science, coupled with more tighter control increases pressure for both proposal development and implementation**
- **Difficulty for contractor community to fully respond to need**
- **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 “Today”

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.

- Are we really on the same page here?

So…

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

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.

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.

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

MB Systems Engineering: So, how is this the *same*?

2.1 The Common Technical Processes and the SE Engine

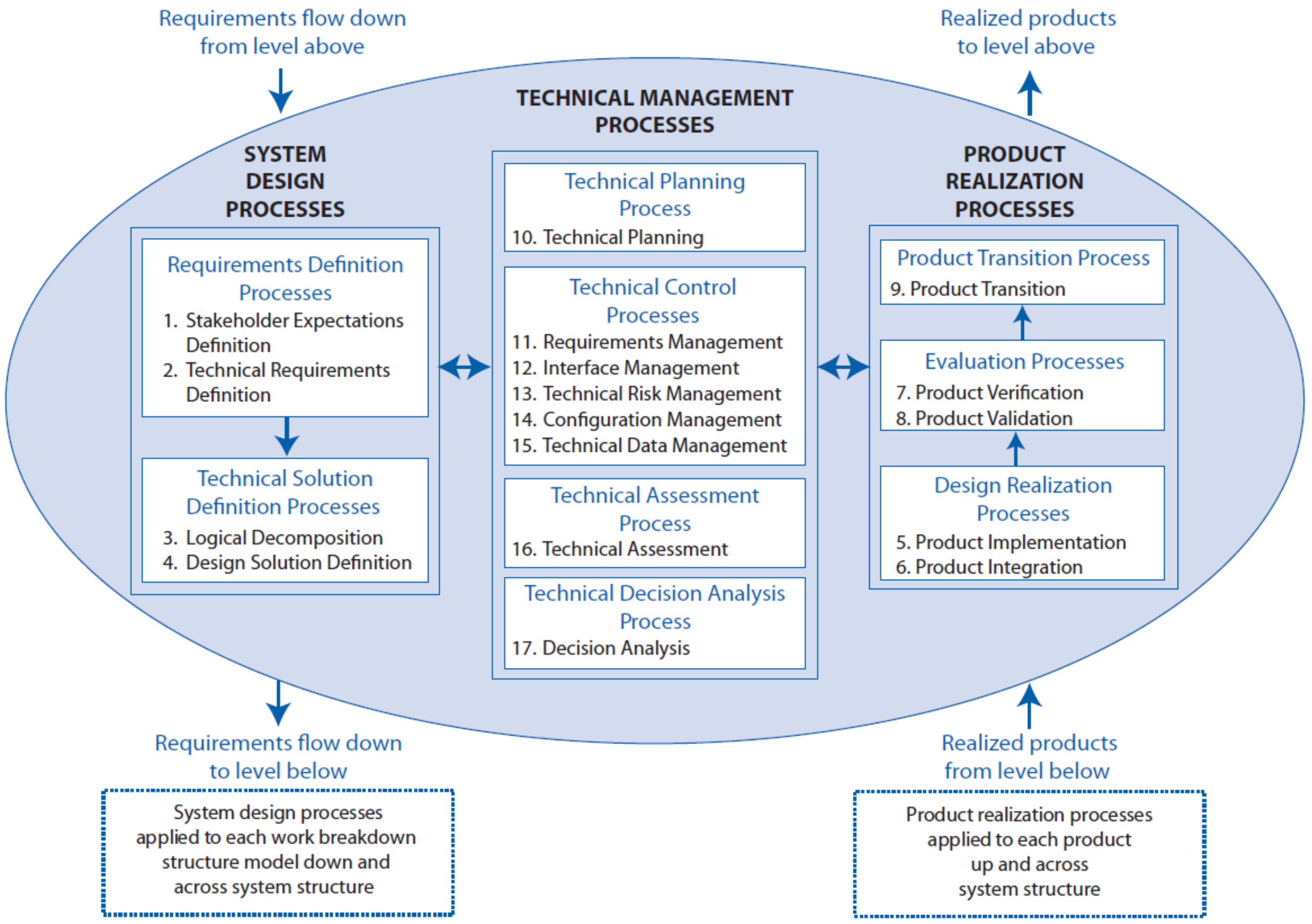


Figure 2.1-1 The systems engineering engine

MB Systems Engineering: So, how is this the *different*?

Requirements Database
- Stakeholder Dialog
- Operational M&S
- Rqmts Analysis
- Rqmts/Arch Tool Linkage
- Reference Arch

Operational Viewpoint (OV)
- Top-Level Structure (Domains)
- Top-Level Behaviors (Use Cases)
- Rqmts Allocation to Domains/Use Cases
- Initial Decomposition (Subdomains)
- Conceptual Data Model≈

Logical/Functional Viewpoint (LV)
- Functional Decomp
- Block Behaviors
- Rqmts Allocation to Blocks, Interfaces, Threads, etc.
- Reference Arch
- Design Trades
- Design Specs
- Logical Data Model

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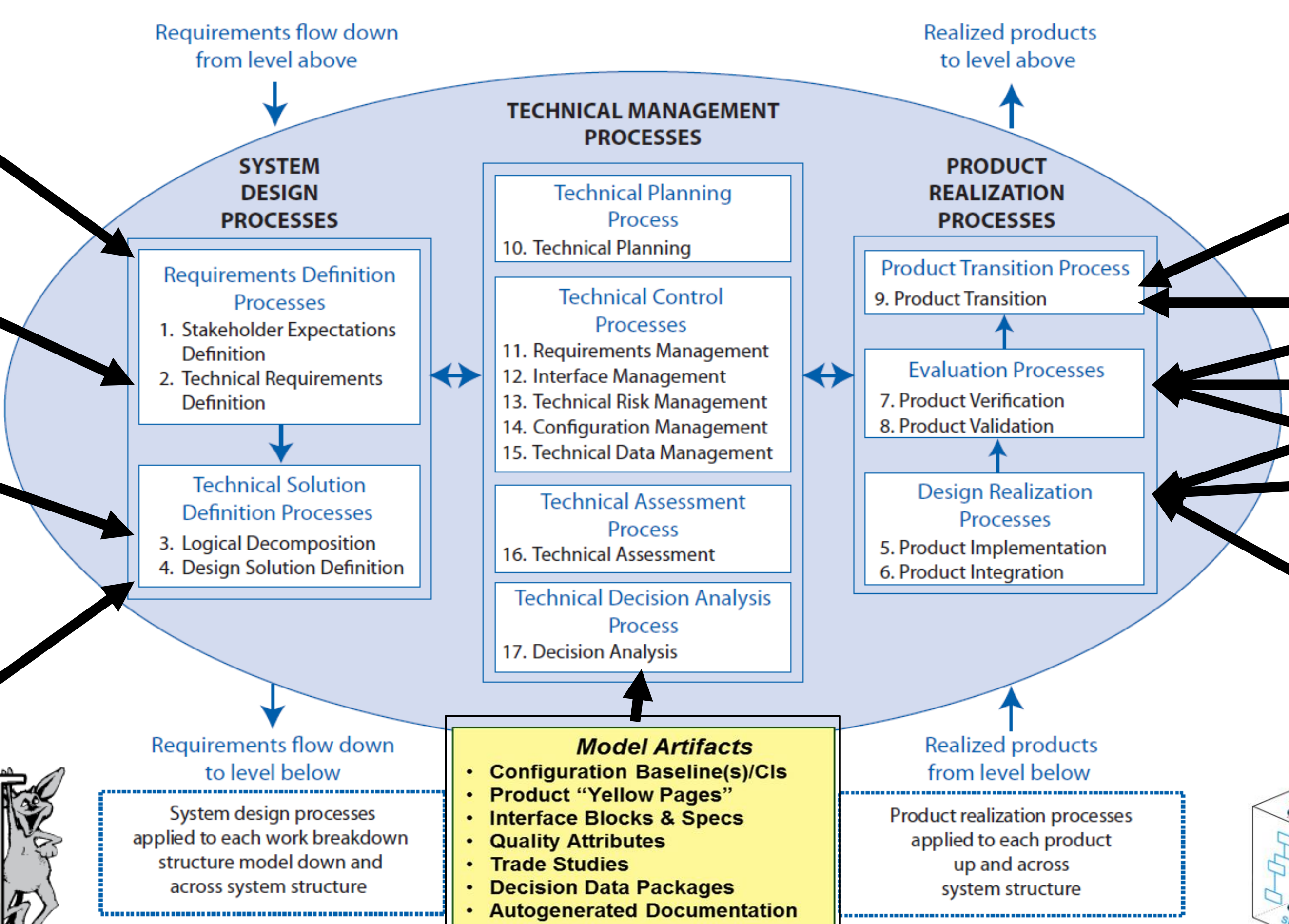


Model Artifacts
- Configuration Baseline(s)/CIs
- Product "Yellow Pages"
- Interface Blocks & Specs
- Quality Attributes
- Trade Studies
- Decision Data Packages
- Autogenerated Documentation

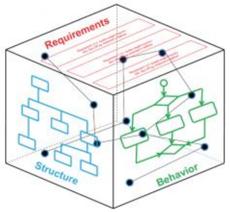


Figure 2.1-1 The systems engineering engine

Tailored Products for Deployment/Sustainment/ Upgrading

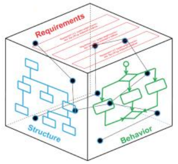
Integrate/Test

Design/Build

Physical/ Virtual Prototype

Physical Viewpoint (PV)
- Product Trades
- Product Specs
- Detailed Timing/ Real-Time Analysis
- Physical Data Model

So, which is it? The *same*, or *different*?



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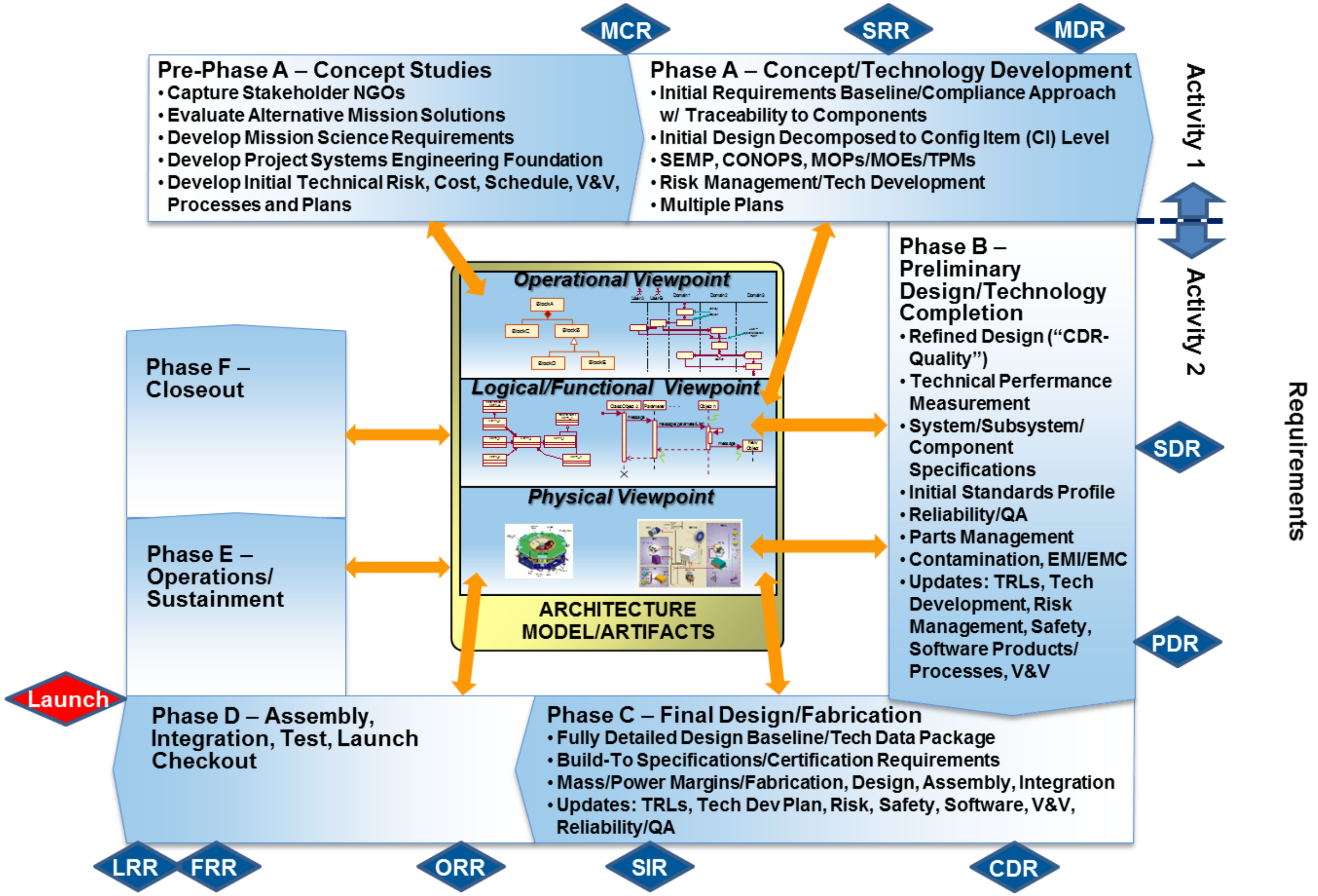
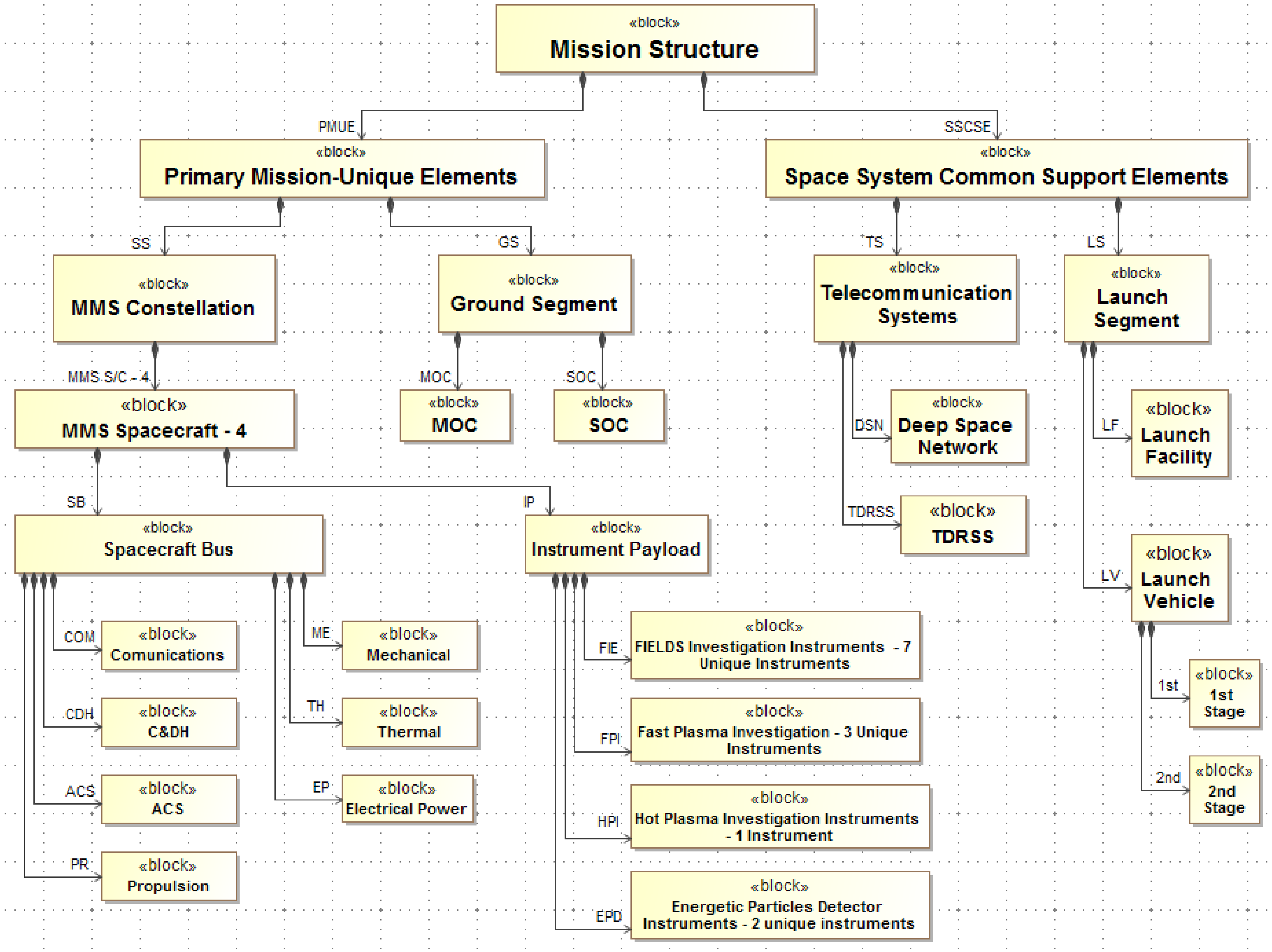
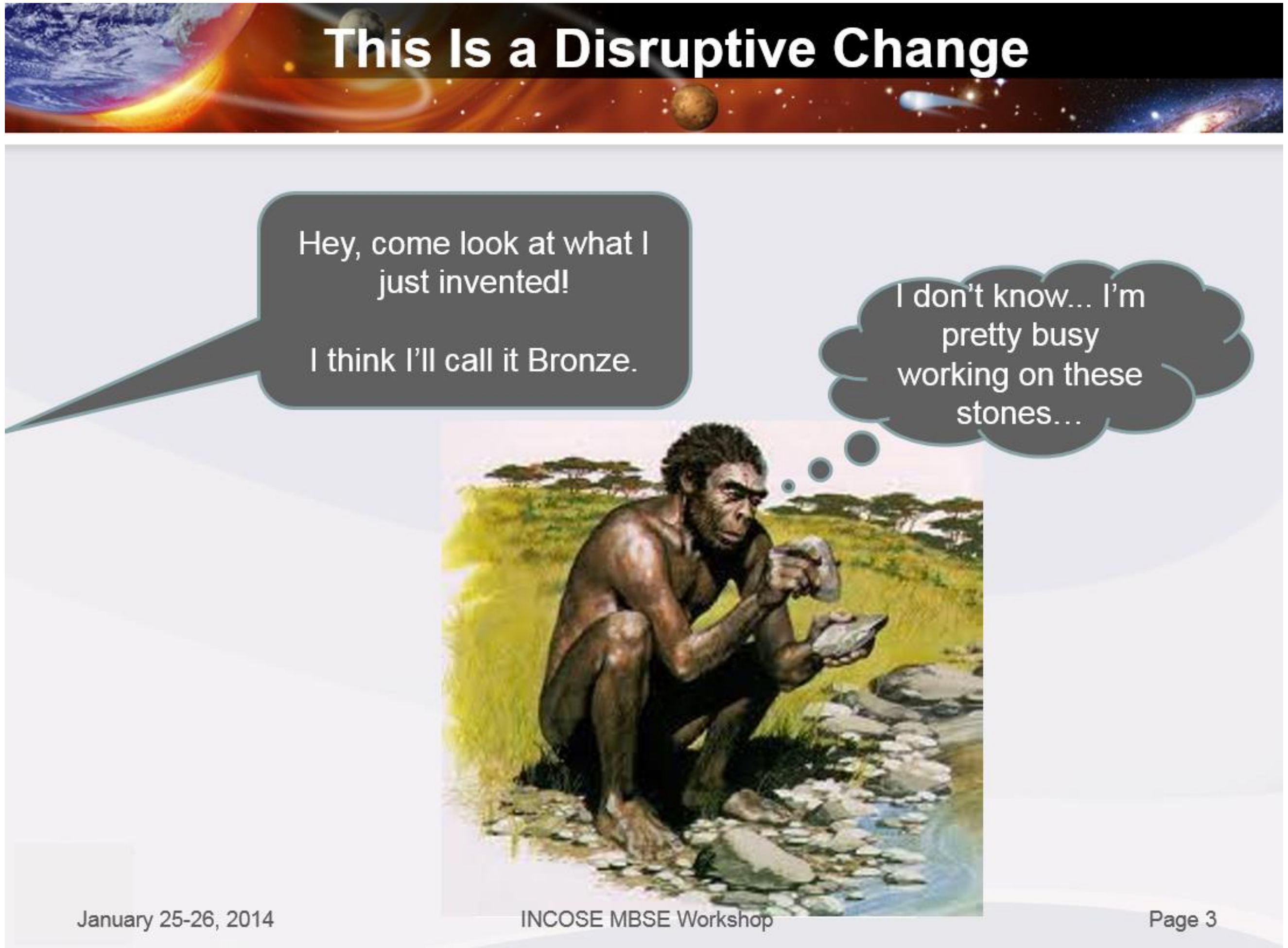


Systems Modeling: So, how is this different?



- The "modeling environment" is a different tool palate than our traditional Power point, Excel, Word
- This diagram is the structural element of the Architecture
- Clearly defined
- Structure, behavior and requirements linked
- ***We need to learn to manage our information differently***

MBSE: A few comments on change and culture



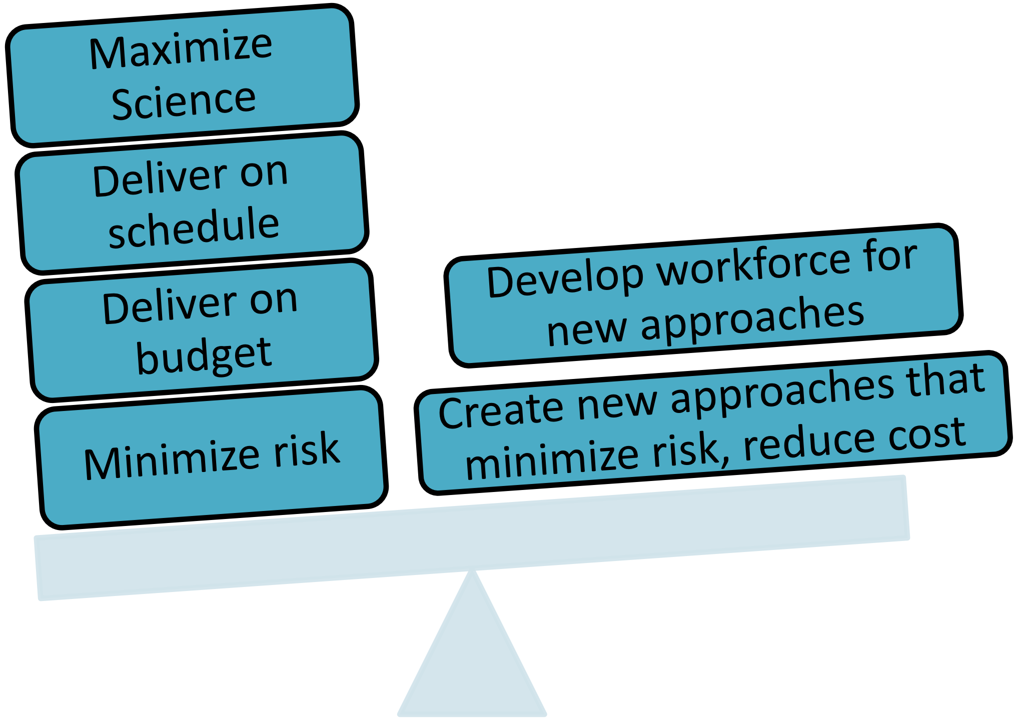
Lessons learned at NASA, specifically JPL, an early adopter and leader of MBSE

- 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

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.

Deliverable:
Project objectives

Development:
Long term Capability
Stewardship



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	Project Policy: Digital methods are standards, and costs are baseline	Engineering Policy: Digital methods are standard practice, manage the transition responsibly and transparently with Program
Program commitment to invest	Project commitment to participate in transformation	Program support work plans are designed for no programmatic impact
Long term program benefits	Business as usual technically	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

So…*Should* the Aerospace Industry "baseline" Model Based Methods?

Moving to MBSE wont's be easy…

… but

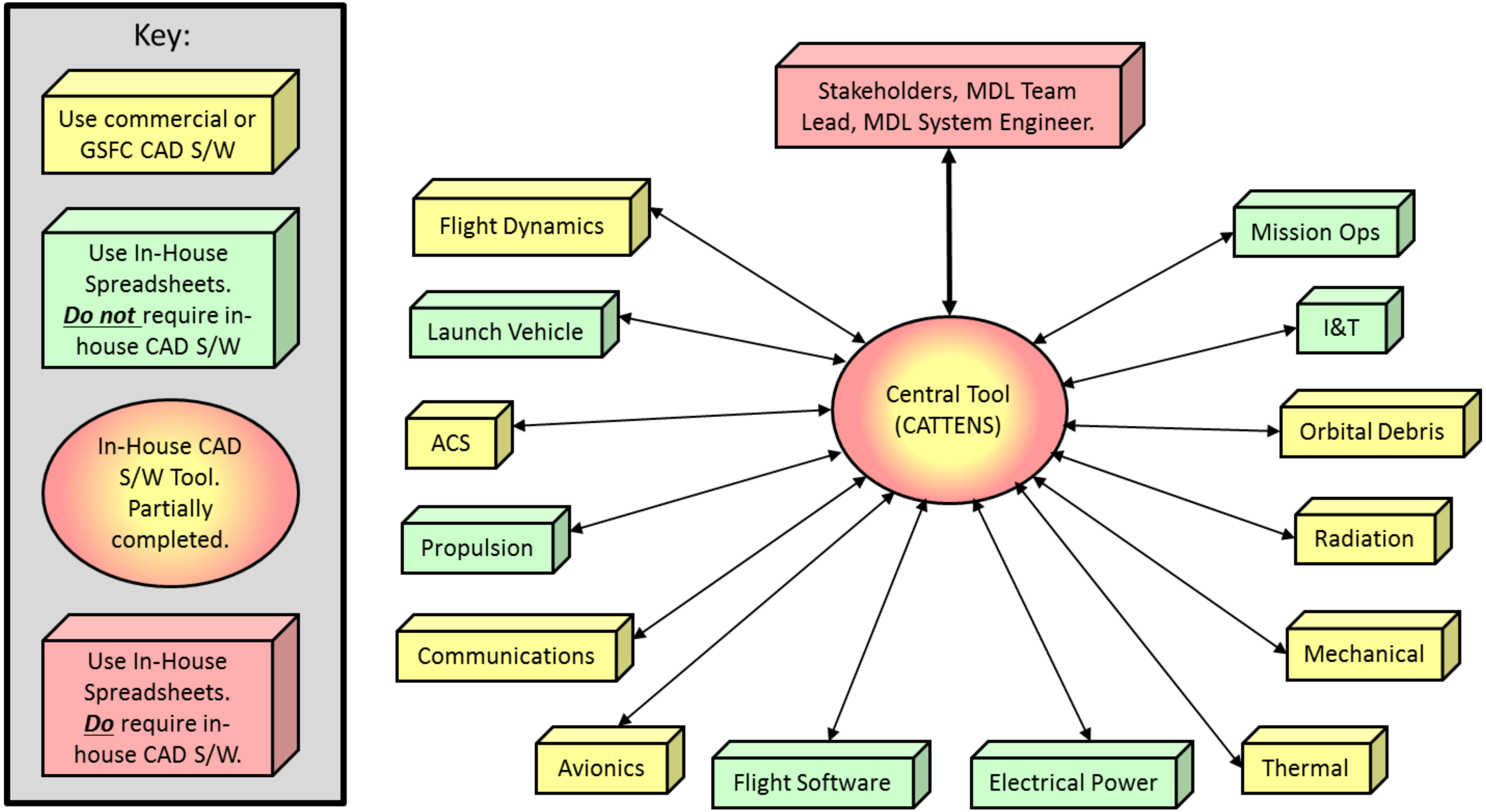
…is should be worth it!

Its too hard to change…

The dreams of yesterday are the hopes of today and the reality of tomorrow

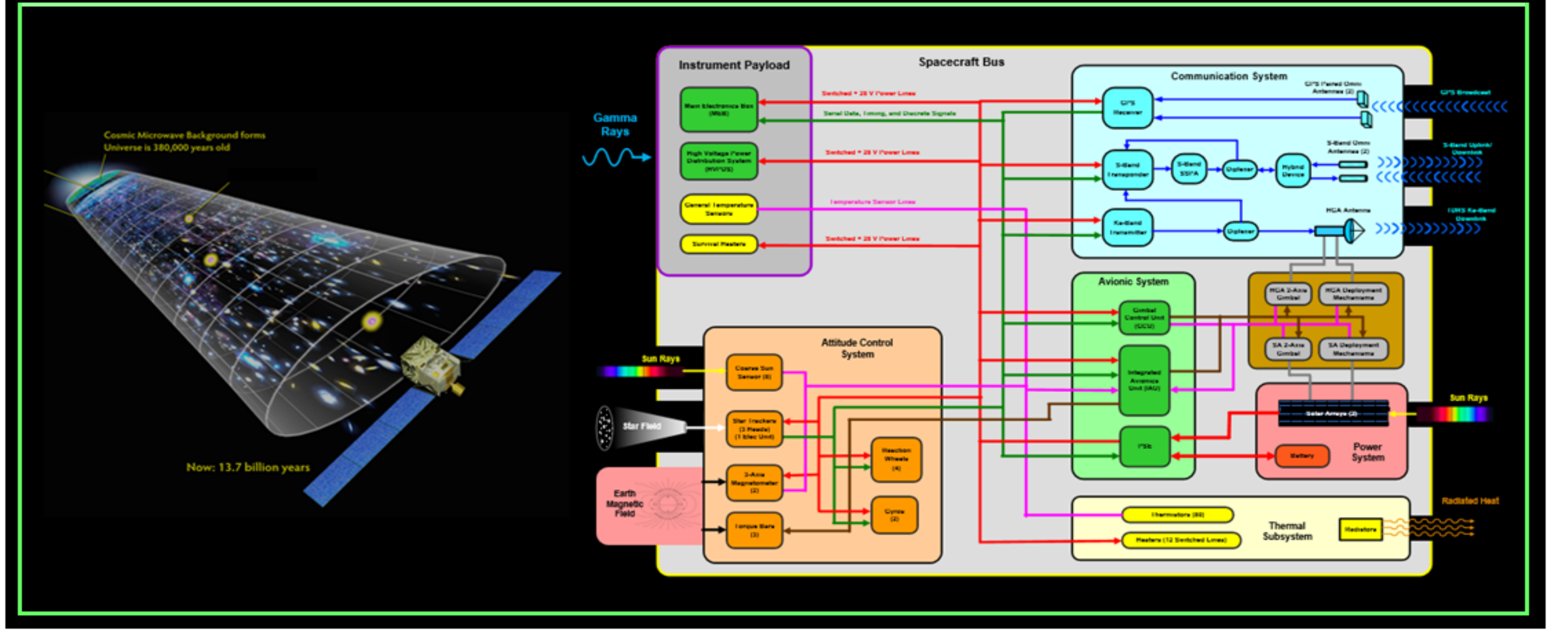
-RHG

State of the Art: Computer Aided Engineering



A Vision: Computer Aided Systems Engineering

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*	



Overview of the GSFC Integrated Design Center (IDC)

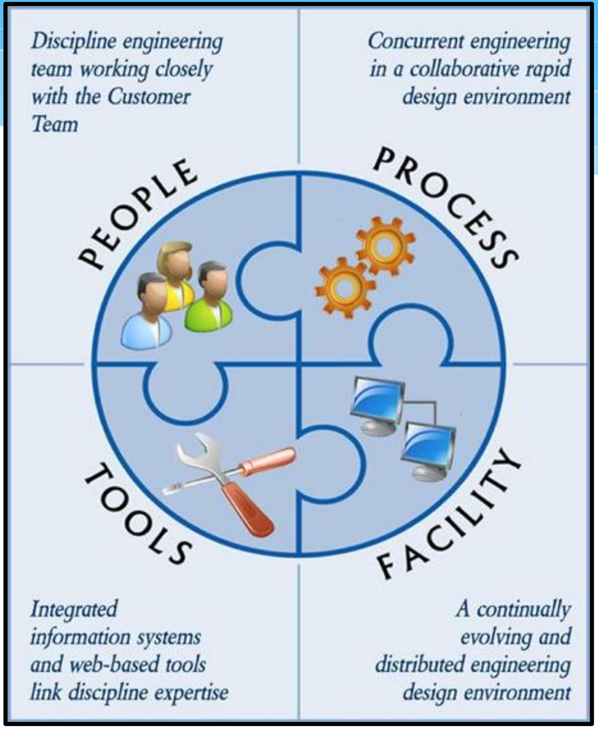
Mission Design Lab (MDL)
Instrument Design Lab (IDL)
Architecture Design Lab (ADL)

Yesterday's dream, today's concept, tomorrow's reality.

Jennifer Medlin Bracken
IDC Manager
301-286-5127
Jennifer.M.Bracken@nasa.gov

Integrated Design Center (IDC)

An environment that facilitates multi-disciplinary, concurrent, collaborative, space system engineering design and analysis activities,



to enable rapid development of science instrumentation, mission, and mission architecture concepts.

Inception and Evolution

Mission Design Lab (MDL)

- Created in 1997
- Initially known as the Integrated Mission Design Center (IMDC)

385 completed studies

Instrument Design Lab (IDL)

- Created in 1999
- Initially known as the Instrument Synthesis & Analysis Laboratory (ISAL)

252 completed studies

Architecture Design Lab (ADL)

- Created in 2012
- Filled need for additional flexibility with broad types of architecture studies

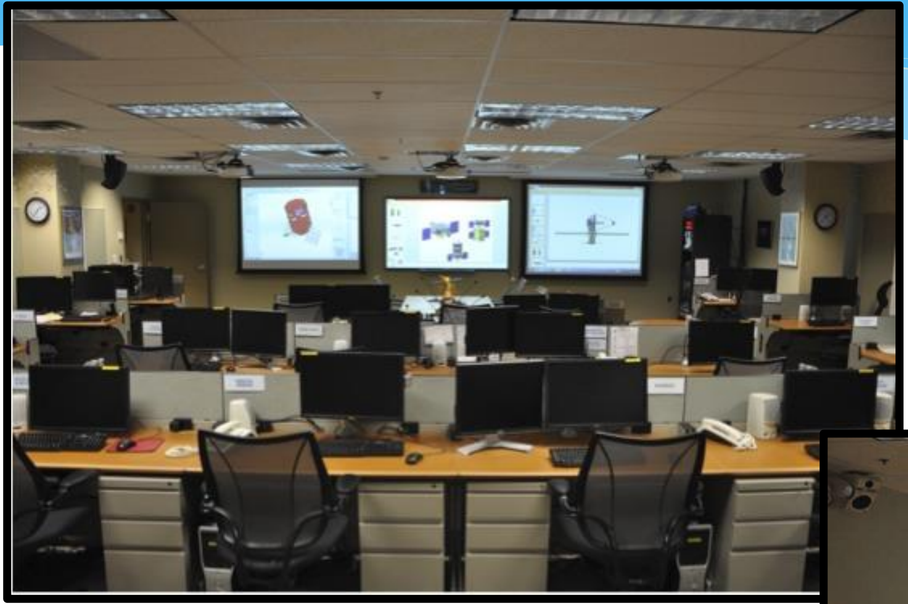
31 completed studies

Integrated Design Center (IDC)

- Created in 2001
- Initially known as the Integrated Design Capability (IDC)

Grand total: 668 completed studies

Where The Magic Happens



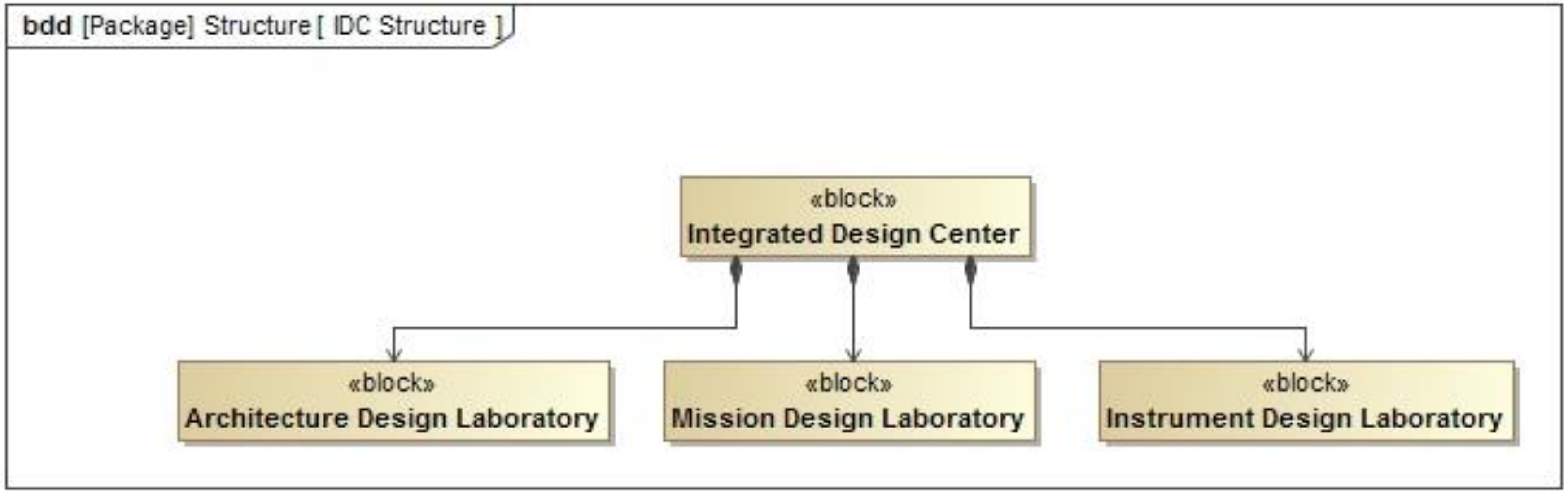
State-of-the-art engineering workstations, software and information technology to ensure engineering excellence.

Mission Design Lab (MDL)

Comfortable, well-equipped workspaces to facilitate dynamic interaction within team

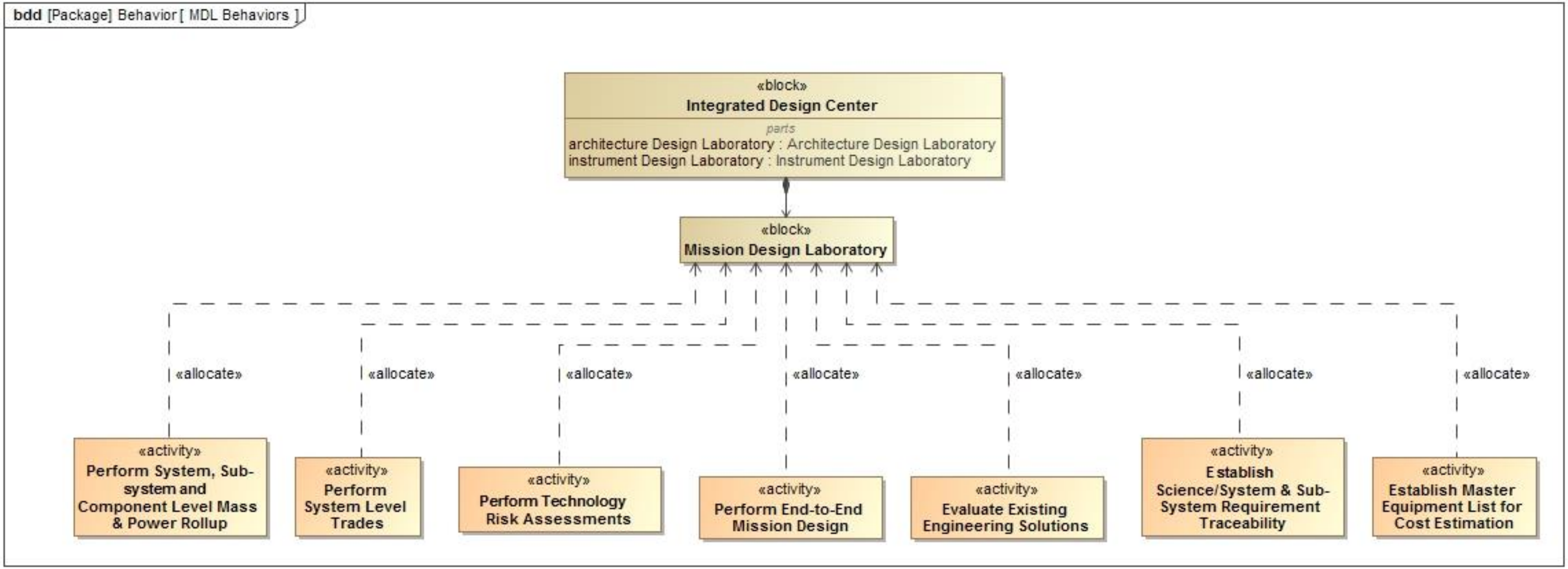
Instrument Design Lab (IDL)

Is this the Death of Power Point…?

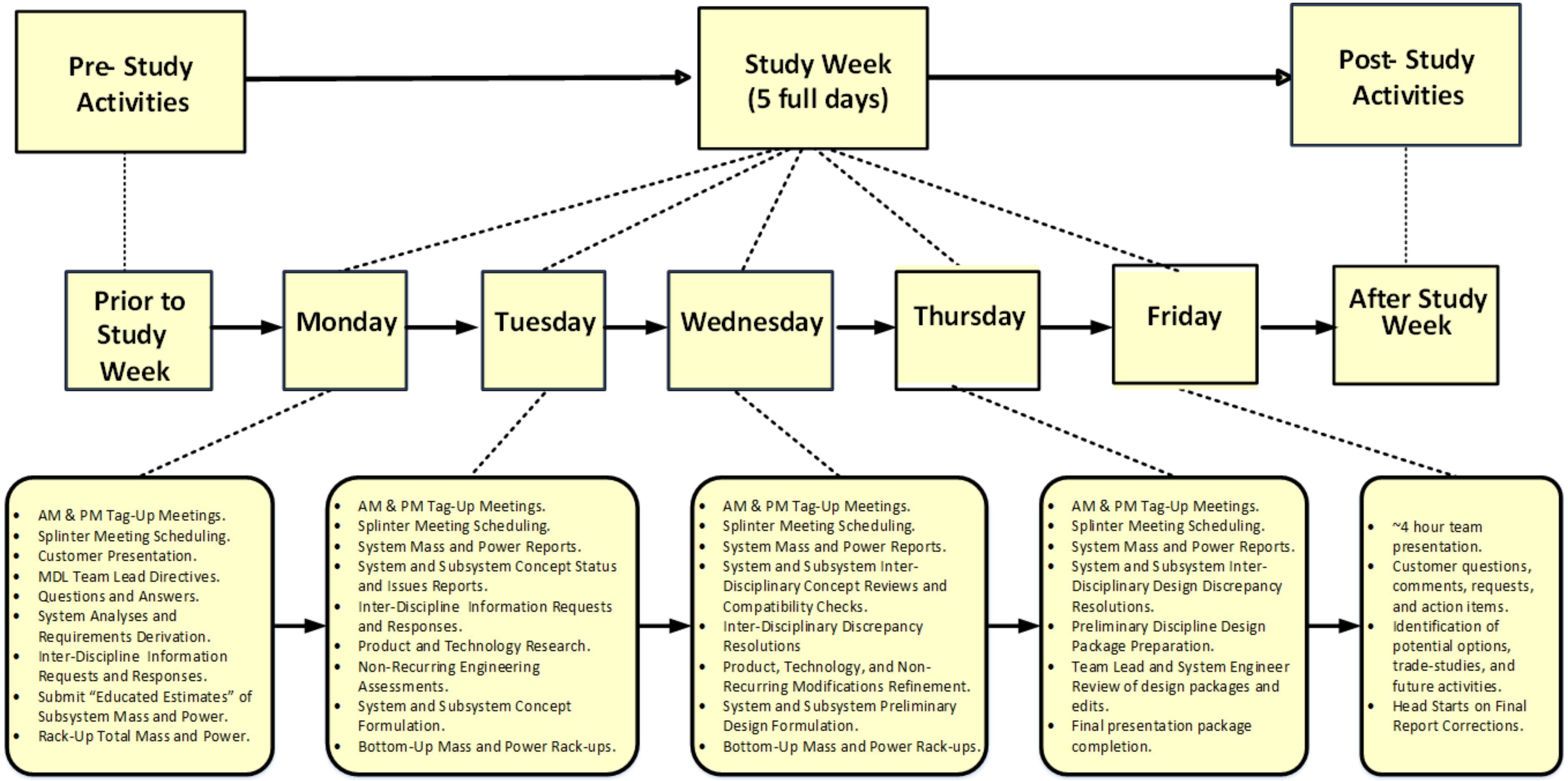


A step in the right direction, tho…not quite yet…

The MDL: “Behaviors” or “Actions” or “Activities”



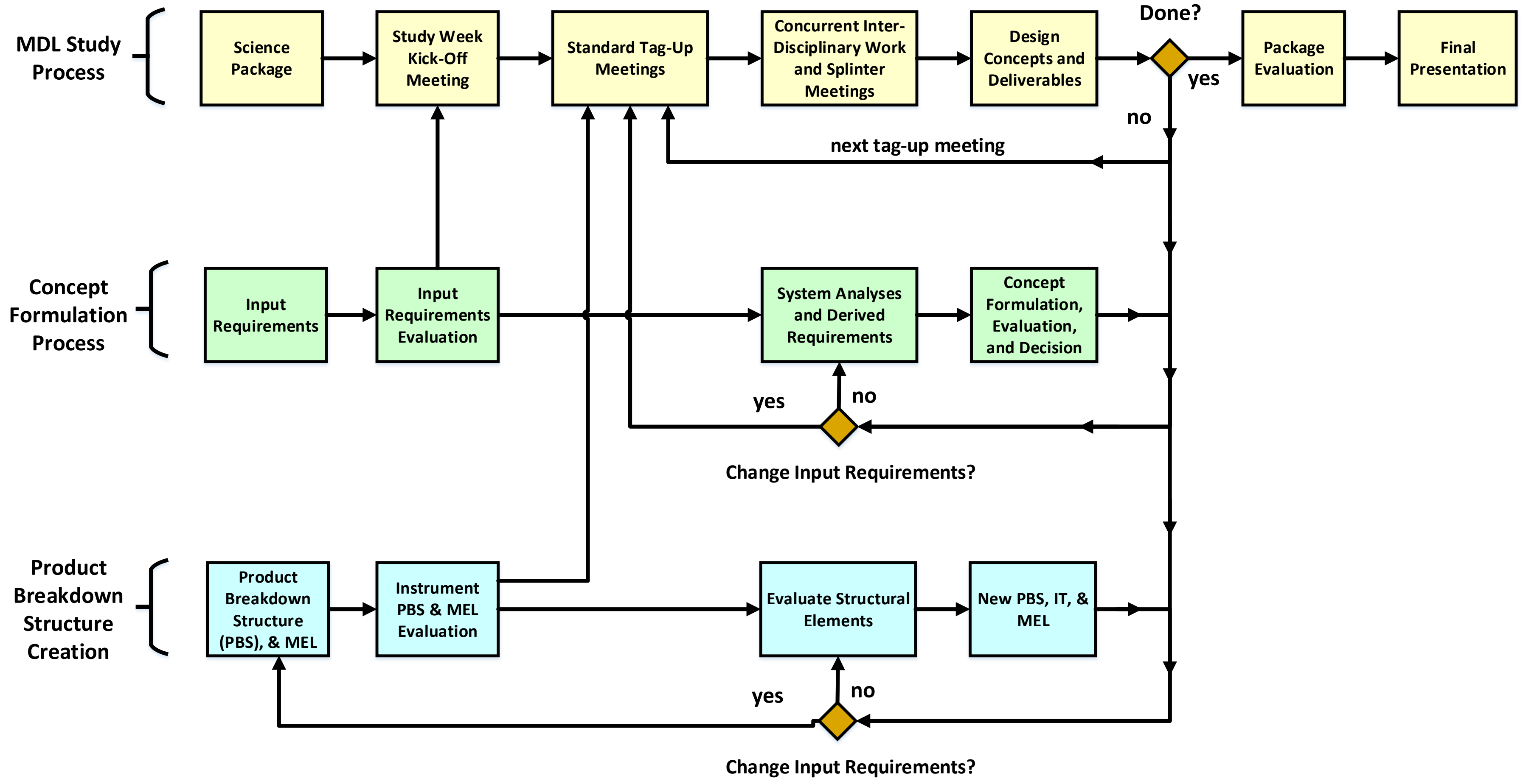
Systems Engineering: Modeling the MDL



The MDL as we understood it, 2017

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

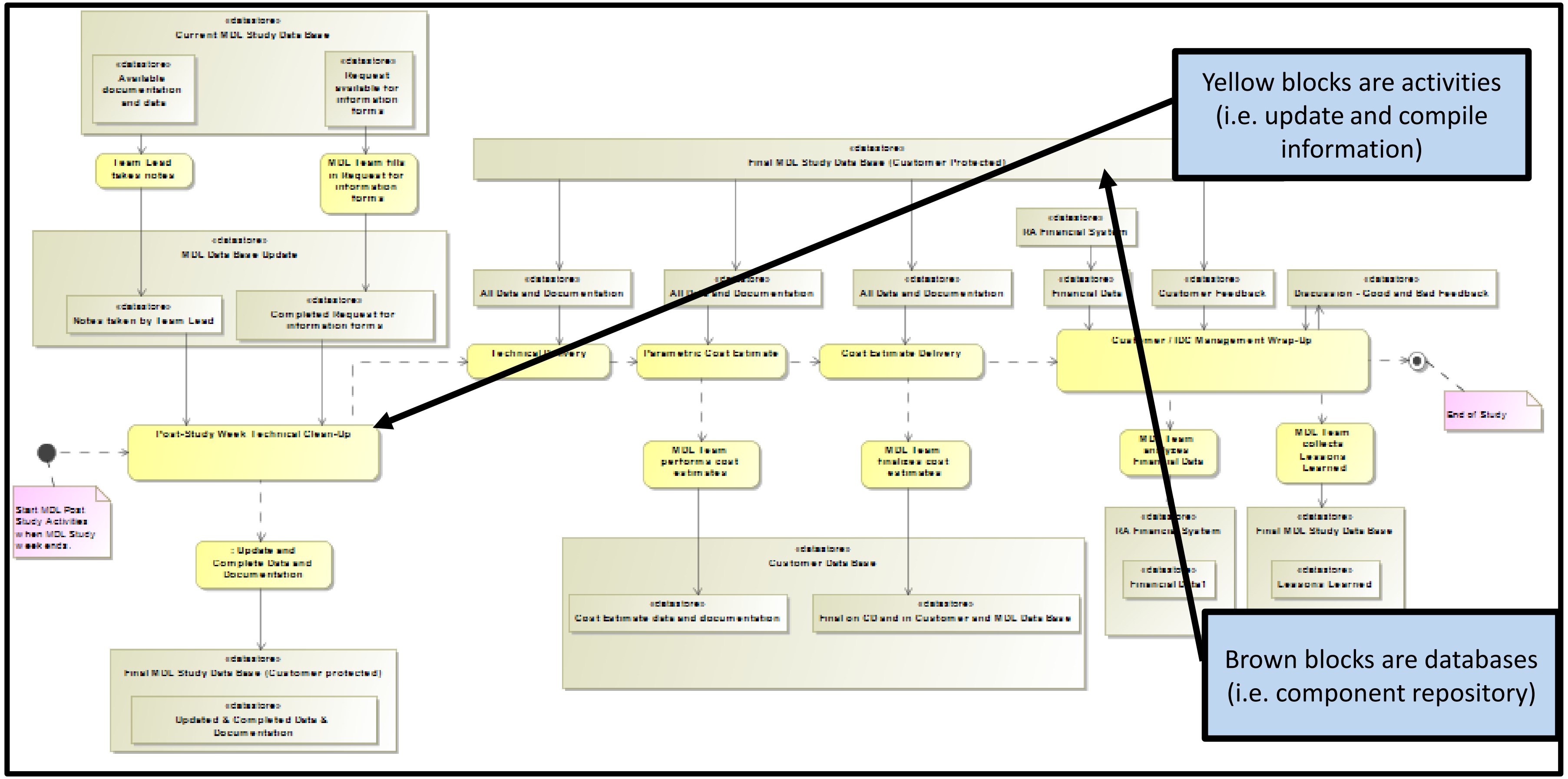
Systems Engineering: Modeling the MDL



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

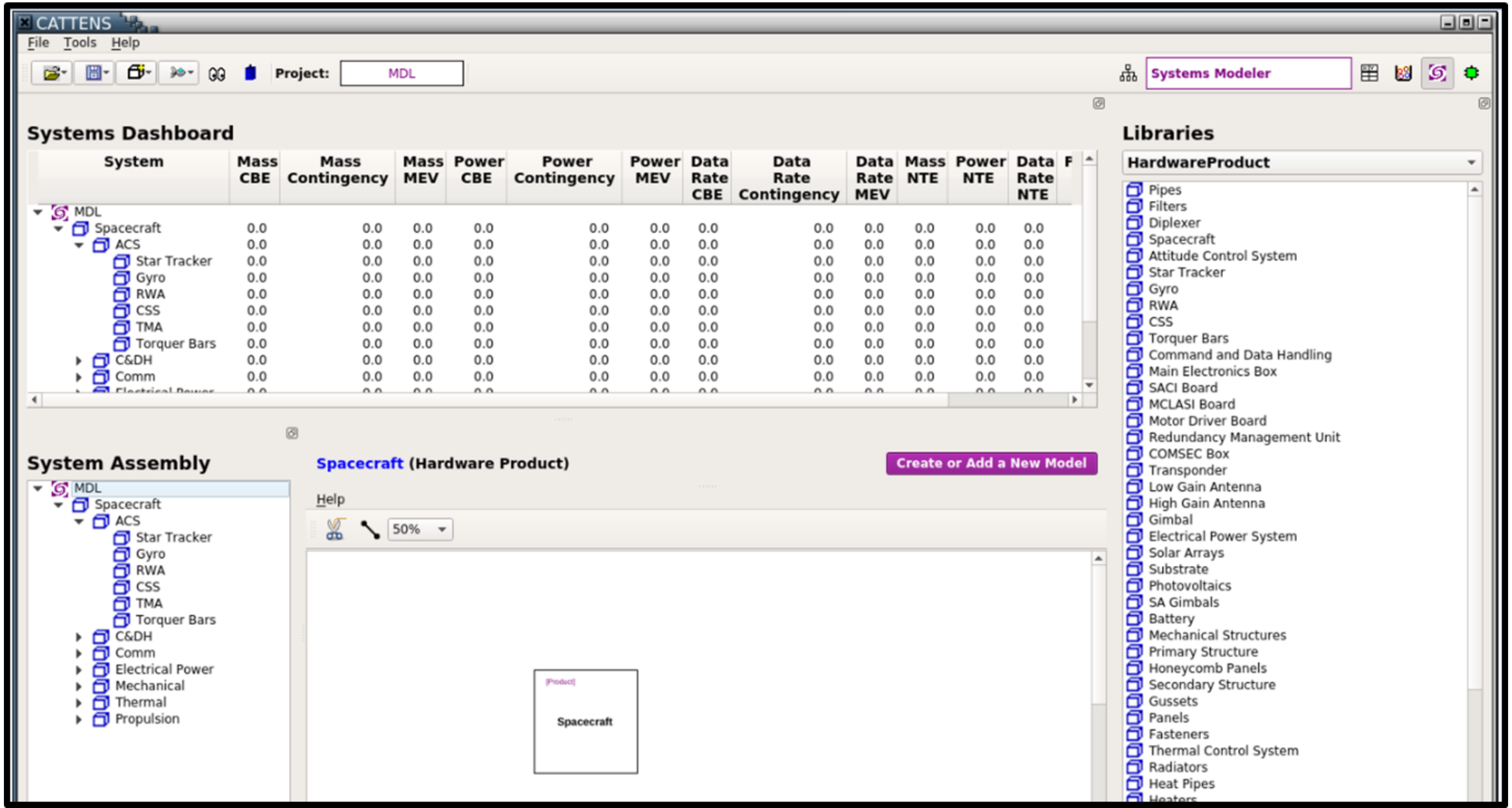
Systems Engineering: Modeling the MDL



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

State of the Art: CATTENS, Product Development



System Development Process: Investment Focus

Facilitation

System Development Process

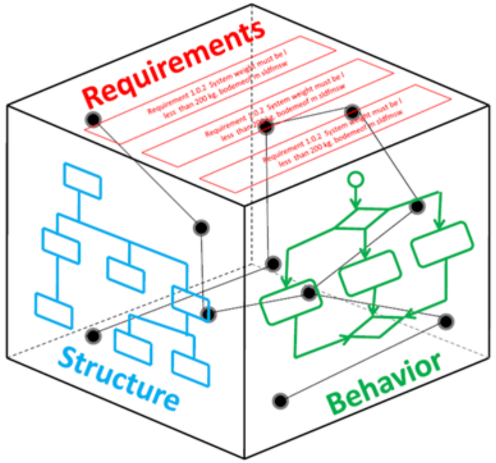
Discipline Engineers

Pre-work

Information Management (PRIME/CATTENS)

MDL Activity (Study)

Analysis Software



Electronic System Model

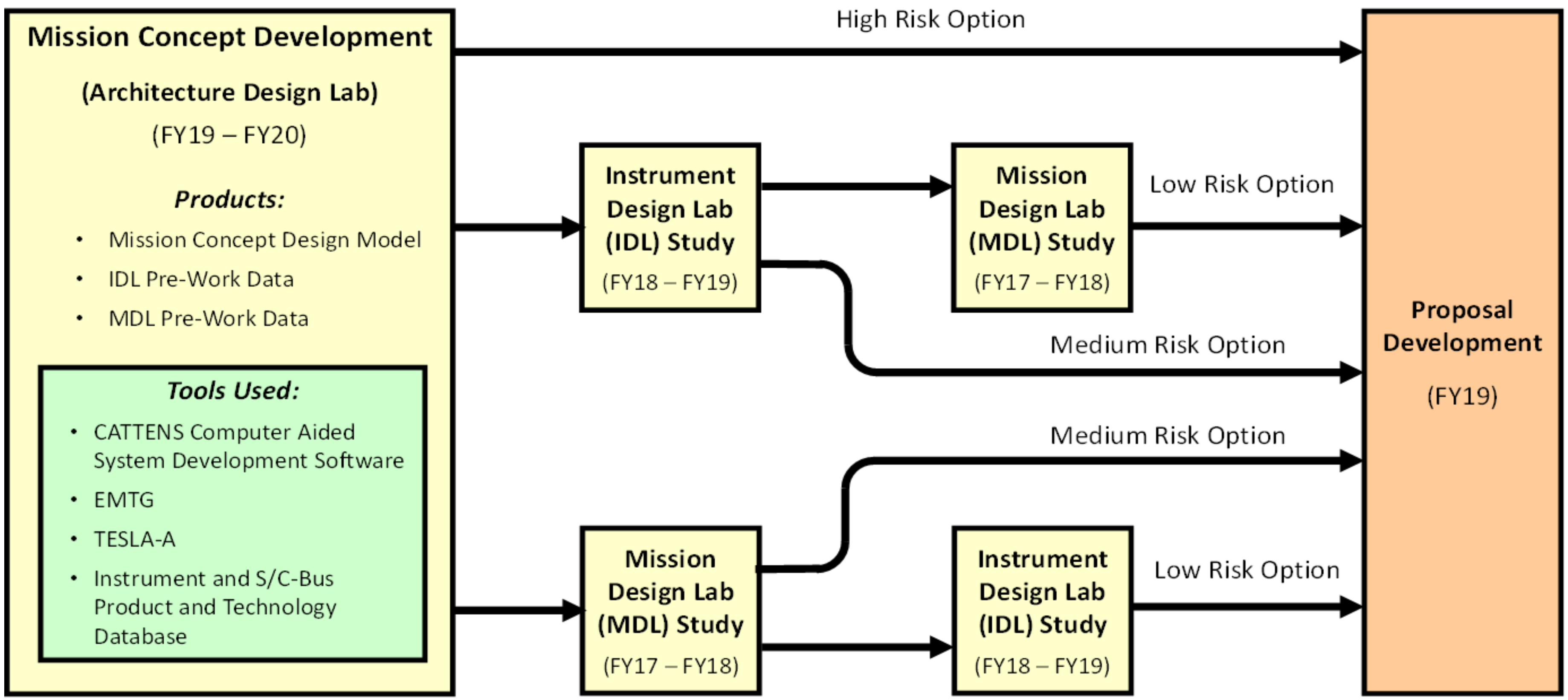
- Science traceability matrix
- Project Need/Goal/Objective
- MEL
- Product Breakdown Structure
- Concept of Operations
- I&T Flow
- …

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

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

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
- System 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***
- An Institutional focus can educate the workforce as we enhance our infrastructure, tools and methods

Questions?