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
James Clerk Maxwell

- 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.

\[ S = -k_B \sum_i p_i \ln p_i \]

where

\[ p_i = \text{Probability of occurring in state } i \]
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.
- 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

• **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!**

---

1 Dr. Thomas Zurbuchen: [https://blogs.nasa.gov/drthomasz/2017/02/13/ambitious-science-driving-innovative-technology/](https://blogs.nasa.gov/drthomasz/2017/02/13/ambitious-science-driving-innovative-technology/)
A Case for Change: OCE SE Capability Leadership

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
A Case for Change: Clear and compelling communication

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.

3 Columbia Accident Report, p. 191
A Case for Change: JPL Systems Engineering; Five System Engineering Challenges

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.
A Case for Change: GSFC Systems Engineering

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
**Systems Engineering environment**

<table>
<thead>
<tr>
<th>SE Role</th>
<th>SE Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leadership</td>
<td>Find the right system solution</td>
</tr>
<tr>
<td></td>
<td>Point everyone to the right solution</td>
</tr>
<tr>
<td>Management</td>
<td>Forecast</td>
</tr>
<tr>
<td></td>
<td>Plan</td>
</tr>
<tr>
<td></td>
<td>Coordinate</td>
</tr>
<tr>
<td></td>
<td>Command</td>
</tr>
<tr>
<td></td>
<td>Organize</td>
</tr>
<tr>
<td></td>
<td>Control</td>
</tr>
</tbody>
</table>
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
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
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.
# Three Examples: Not a Modeling Clinic

| Model Based Sounding Rocket | • Represents a specific mission from the Sounding Rocket Program (WFF)  
|                           | • Part of OCE MBSE Pathfinder effort  
|                           | • Attempts to create a model that supports the design review (communication)  |
| Antenna Deployment         | • Case study: Represents an antenna sub-system (IV&V, assurance)  
|                           | • Simulates deployment operation to check logic (Analysis, integration)  
|                           | • Enhanced communication with software team (Communication)  |
| MMS mission                | • Early FY ‘18 IRAD work to model MMS mission  
|                           | • Growing awareness of model use in early lifecycle  
|                           | • 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
- Heliophysics
- 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 Modeling and Tools
  - Products (Hardware and Software Aspects: Structural, Behavioral, Requirements, Parametric)
  - Resources (Human, Facilities, Equipment, Tools, Funding)
  - Processes (Life-Cycle, Schedules, Procedures, Operations)

Mission Design and Development Modeling
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

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

Key:
- Use commercial or GSFC CAD S/W
- Use In-House Spreadsheets. **Do not** require in-house CAD S/W
- In-House CAD S/W Tool. Partially completed.
- Use In-House Spreadsheets. **Do** require in-house CAD S/W.

Central Tool (CATTENS)

- Stakeholders, MDL Team Lead, MDL System Engineer.
- Flight Dynamics
- Launch Vehicle
- ACS
- Propulsion
- Communications
- Avionics
- Flight Software
- Electrical Power
- Thermal
- Mission Ops
- I&T
- Orbital Debris
- Radiation
- Mechanical
Vision: A systems engineering tool for the MDL
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

- 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
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

<table>
<thead>
<tr>
<th>Process efficiencies:</th>
<th>Enhanced quality and integrity in system architectures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced effort, time and cost in executing SE processes</td>
<td>• Improved and earlier detection of design errors, wrong or missing requirements, conflicting interface definitions, etc.</td>
</tr>
<tr>
<td></td>
<td>• Improved communication and shared understanding among disciplines, teams, and stakeholders</td>
</tr>
<tr>
<td></td>
<td>• Improved tools for requirements analysis, allocation, and tracing</td>
</tr>
<tr>
<td></td>
<td>• Payoffs from Object-Orientation - Abstraction/Inheritance, Modularity, Loose Coupling, Interface Management, and others</td>
</tr>
<tr>
<td></td>
<td>• Framework for modeling and simulation at multiple levels</td>
</tr>
</tbody>
</table>

- 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
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)

Input State
Products, Resources, and Processes from Previous Iteration

Products
(Hardware and Software Aspects: Structural, Behavioral, Requirements, Parametric)

Interrelationships
(Information Flow Relationships Node)

Output State
Products, Resources, and Processes To Next Iteration

Resources
(Human, Facilities, Equipment, Tools, Funding)

Processes
(Life-Cycle, Schedules, Procedures, Operations)

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”
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

**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 Decomposition
- Block Behaviors
- Rqmts Allocation to Blocks, Interfaces, Threads, etc.
- Reference Arch
- Design Trades
- Design Specs
- Logical Data Mode/

**System Design Processes**

**Requirements Definition**
1. Stakeholders
2. Expectations

**Technical Solution**
3. Logical Decomposition
4. Design Solution

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

**Product Realization Processes**

**Product Transition**
9. Product Transition

**Evaluation**
8. Product Validation
7. Product Verification

**Design Realization**
6. Product Integration
5. Product Implementation

**Products from below**

**Products to next level**

**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
Model Based Systems Engineering
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

Maximize Science
Deliver on schedule
Deliver on budget
Minimize risk

Development: Long term Capability Stewardship

Develop workforce for new approaches
Create new approaches that minimize risk, reduce cost
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.
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?