Jet Propulsion Laboratory
California Institute of Technology

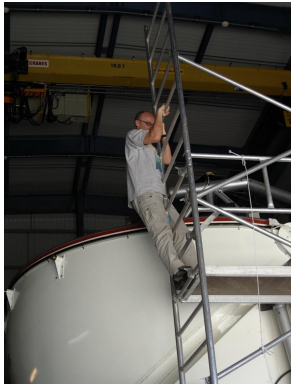
Connecting the V for a Connected World

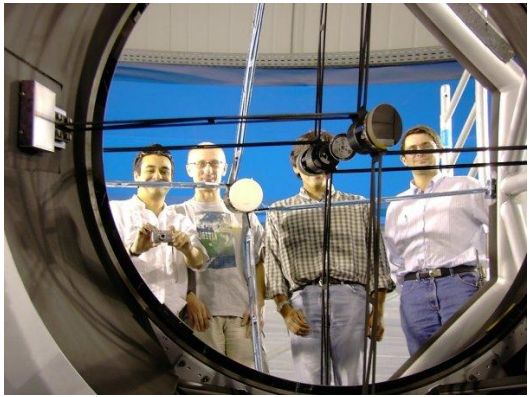
Robert Karban
Jet Propulsion Laboratory, California Institute of Technology

Austrian Software Day, Sep 29 2020, Vienna, Austria

Who is Robert?

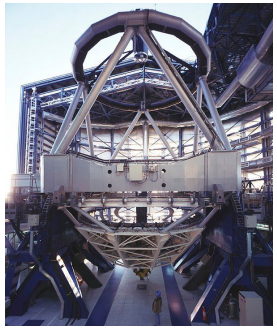
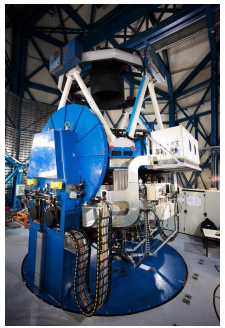
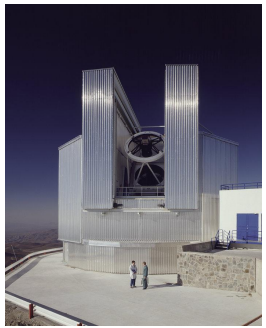
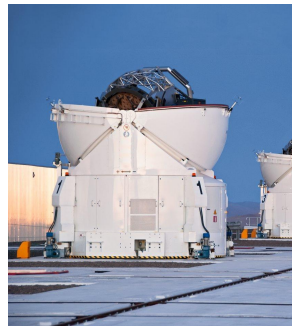
- CAE Systems and Software Environment Chief Engineer at JPL
- Member of INCOSE, SysML RTF, SysMLv2
- Formerly Control System/Software Engineer and Architect at:
    - European Southern Observatory (ESO) – Germany, Chile
    - CERN – Switzerland/France
    - Siemens Healthcare - Austria
- M.Sc. Computer Science (Austria)



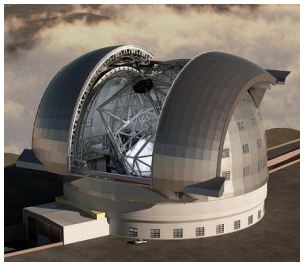
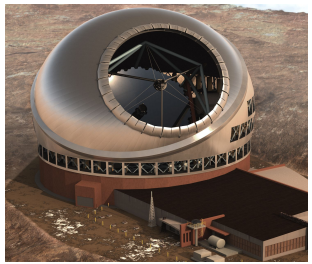



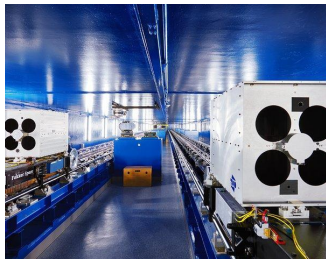

Telescopes and Instruments Robert worked on (~20 FTEs)

- 4 x Very Large Telescope – 8m
- 4 x Auxiliary Telescope – 1.8m
- 1 x Very Large Interferometer – 130m - 200m
- 2 x Survey Telescope – 4m
- 55 x Radio Telescope – 12m - 15m
- 1 x 3.6m Telescope – 3.6m
- PRIMA and APE instruments
- 1 x NTT – 4m
- 1 x ELT – 39m
- 1 x TMT – 30m

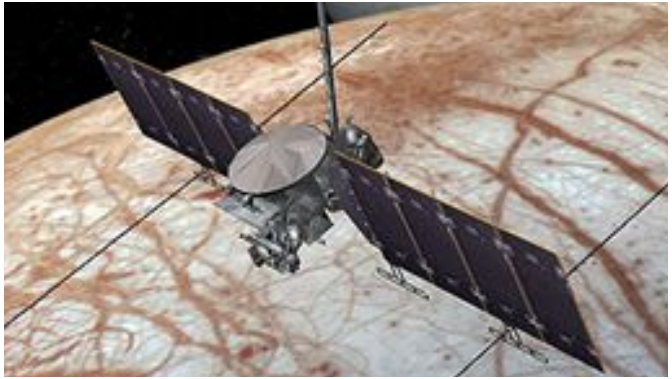


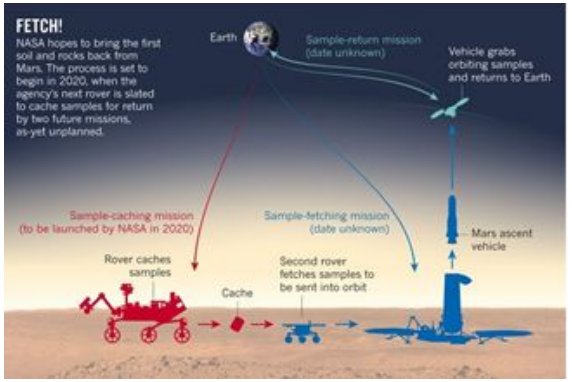






Space Missions

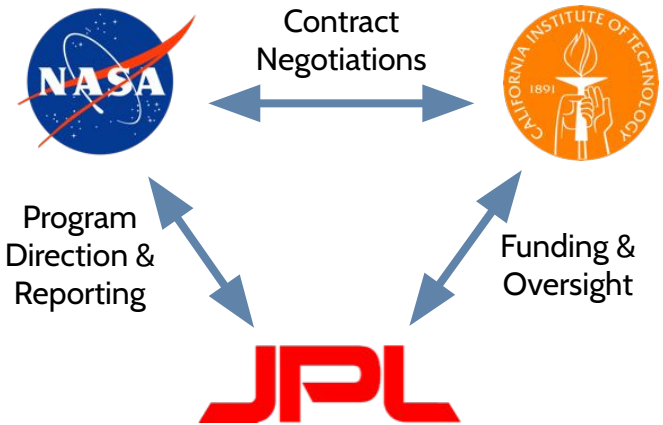
- Europa Clipper
- Europa Lander Mission Concept
- M2020
- Planned Mars Sample Return
- Psyche

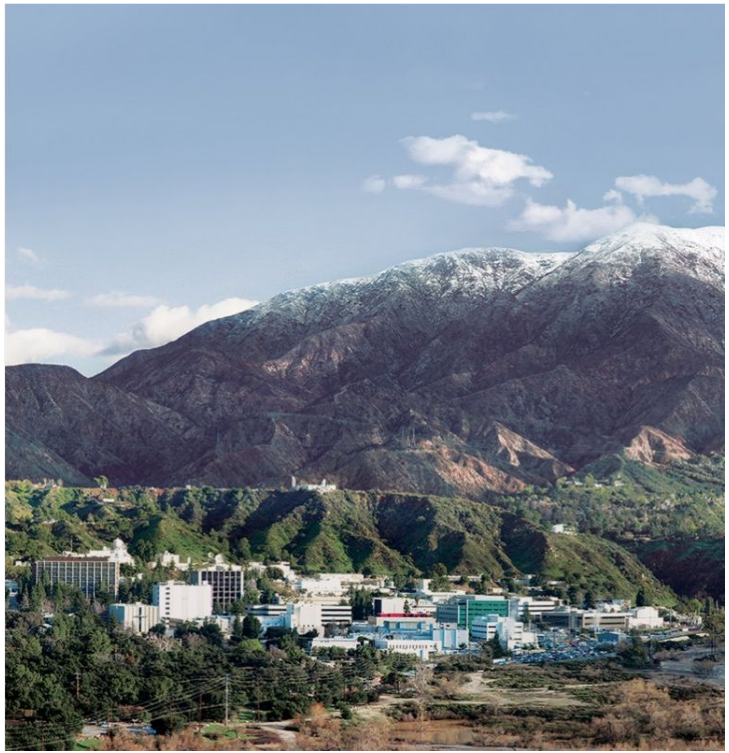




NASA Jet Propulsion Laboratory

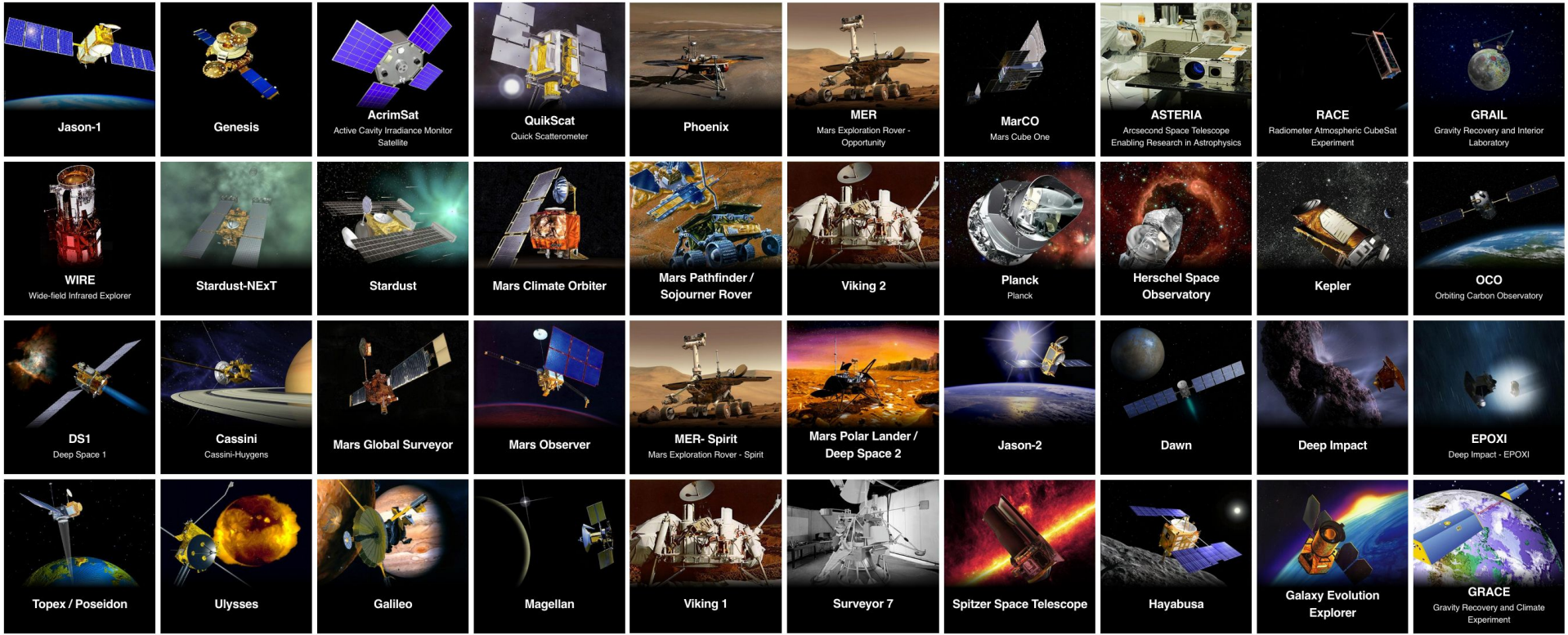
- Located in Pasadena, CA
- NASA-owned *"Federally-Funded Research and Development Center"*
- University-operated
- ~6,000 employees





JPL Campus in Pasadena, CA

Past Missions



Source: https://www.jpl.nasa.gov/missions/

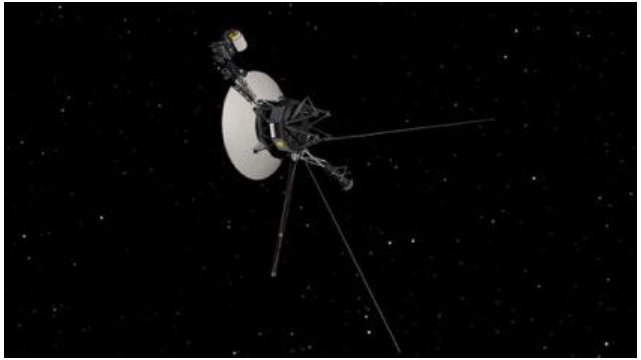
Current Missions

Source: https://www.jpl.nasa.gov/missions/

Some Notable Firsts

Surveyor 1, First soft landing on the moon

Viking, first landing on another planet



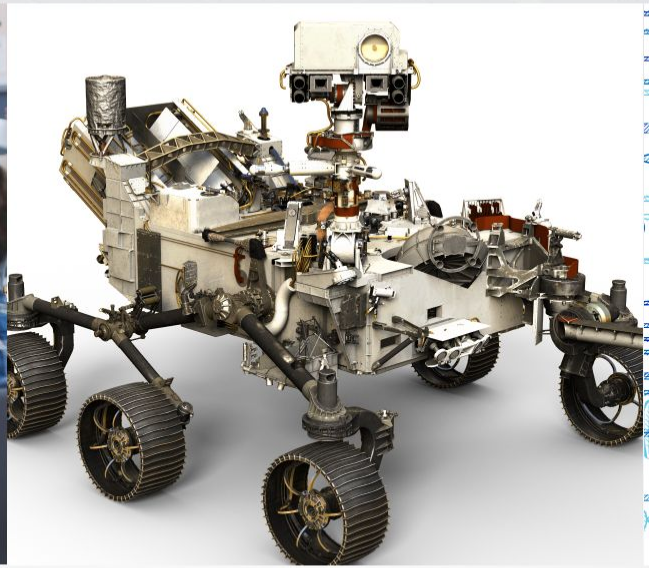
Voyager 1, First interstellar traveler

Continuous presence on Mars since 1997

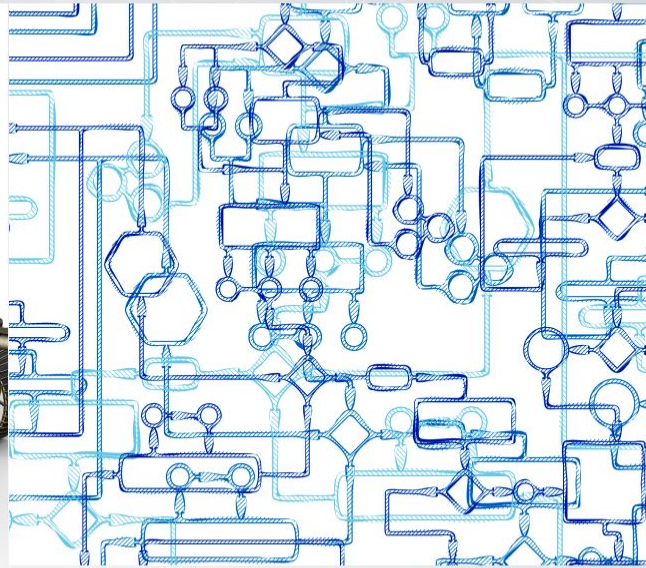
Systems and Software Engineering at JPL

Systems Engineers guide the concurrent collaborative design of complex technical systems

Leadership



Architect and Design
Cyber-Physical Systems



Manage Complexity

Flight project teams are large

A project starts simple

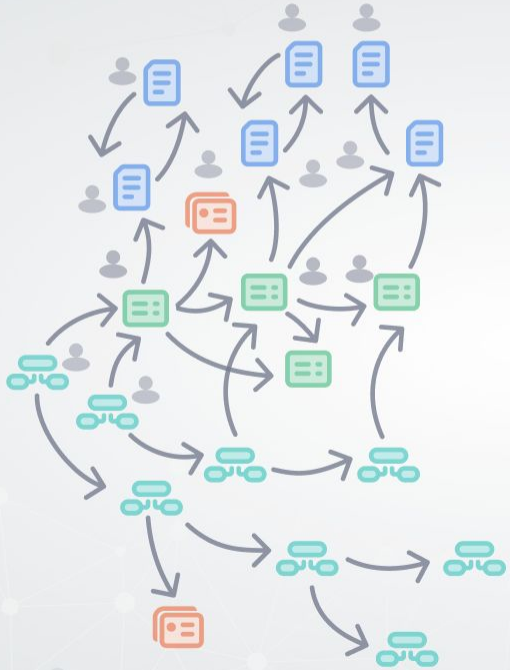
Engineers iterate on their models

Systems engineers enter this data into their rollup

They add it to a document and get inputs from others

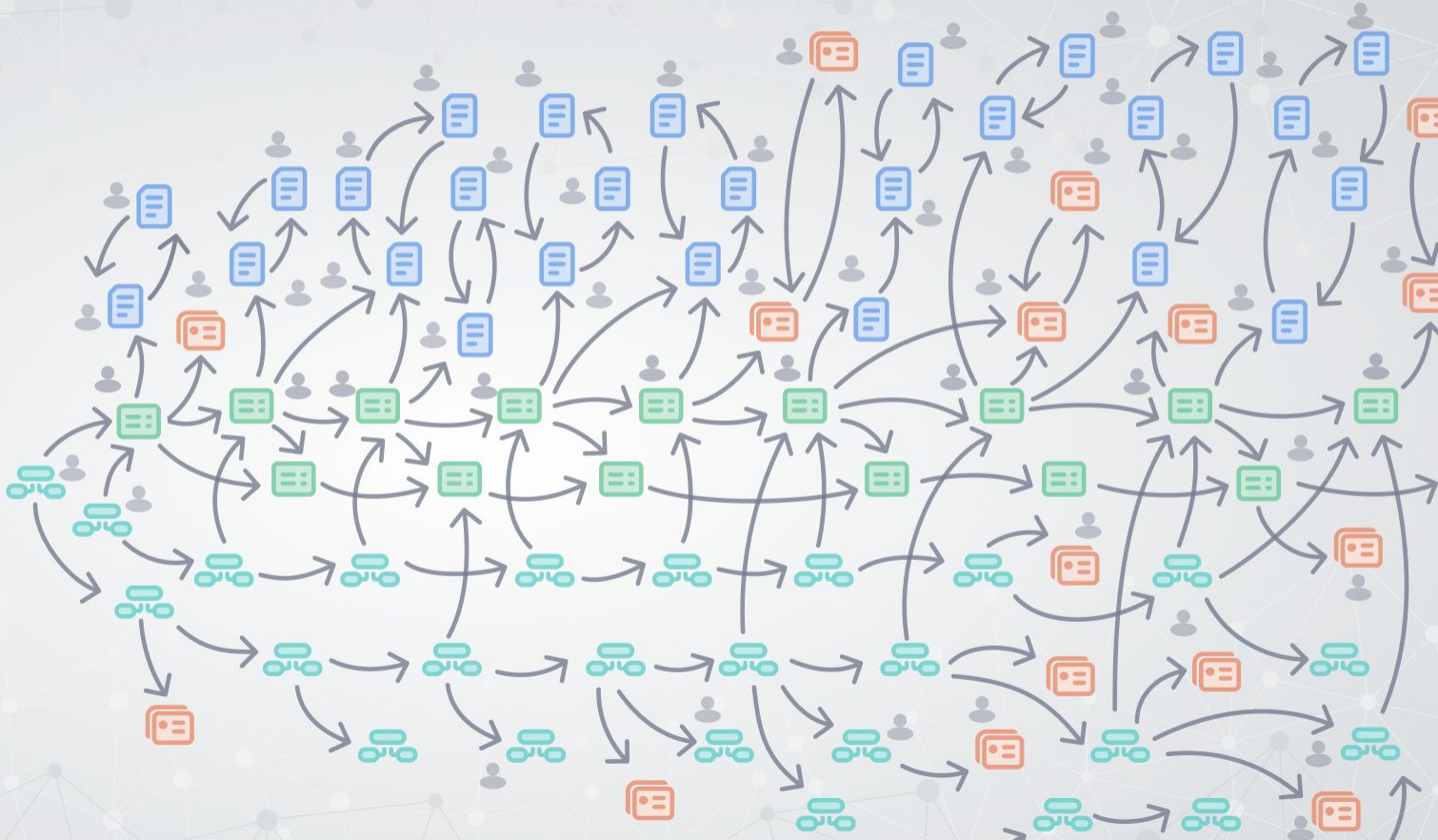
And add it to a spreadsheet to track it over time

It can get complicated quickly

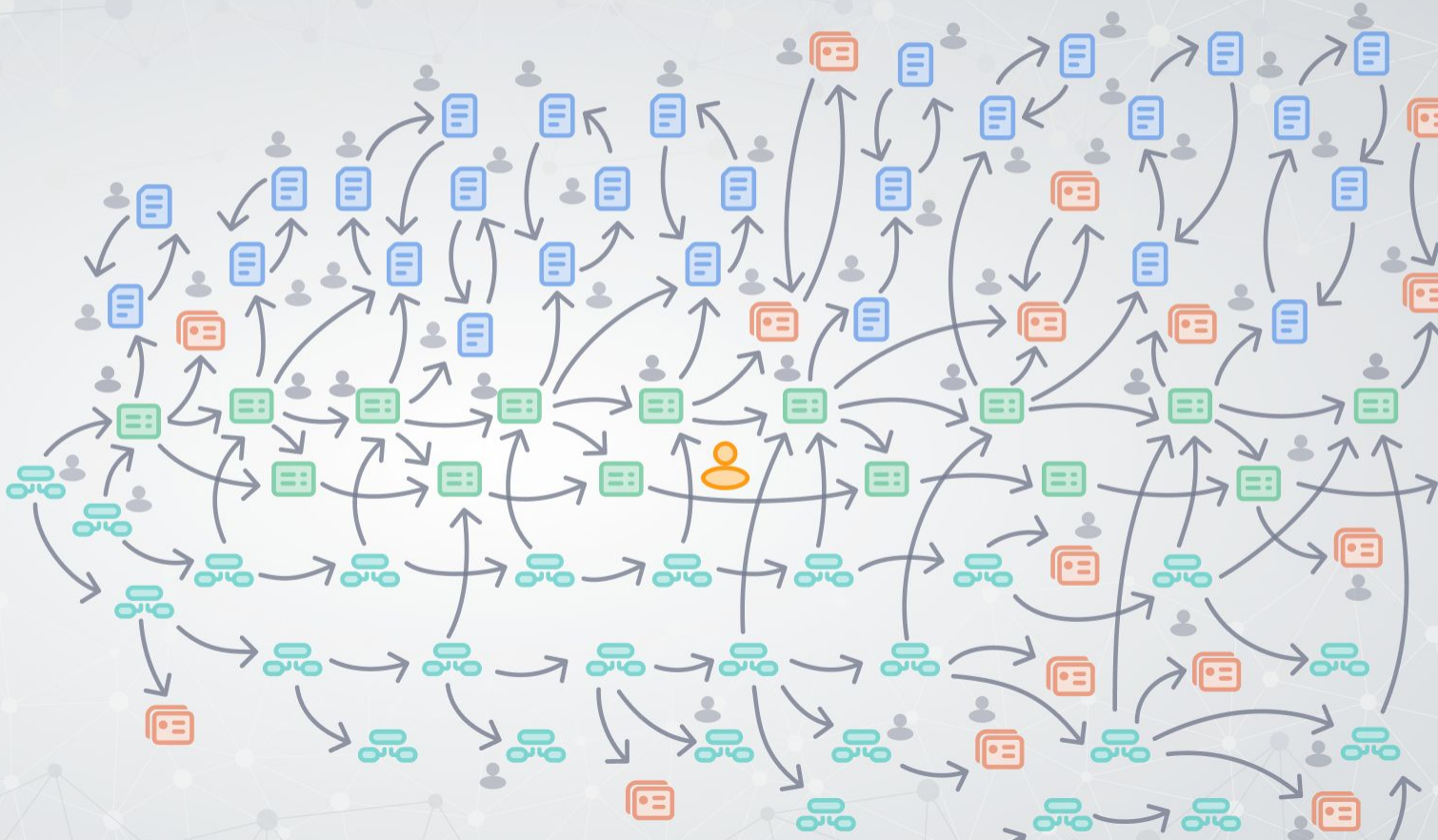


It can get complicated quickly

It can get complicated quickly



And become overwhelming...



> **Using engineers as information janitors isn’t the best use of their skill.**

JPL Systems Engineer

Real engineering vs. overhead

Repetitive Data Entry

Version Confusion

Constant Searching

Topic: Model Based Engineering

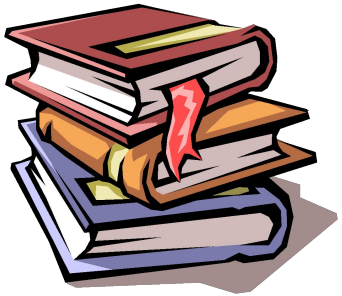
Making models the engineering driver

Model Based Systems Engineering

- MBSE is the formalized application of modeling techniques to support system requirements, design, analysis, verification, validation and documentation activities
- MBSE expresses a system using a Systems Modeling Language (e.g. SysML)
- MBSE is often applied with a method like Object Oriented System Engineering Method (OOSEM)

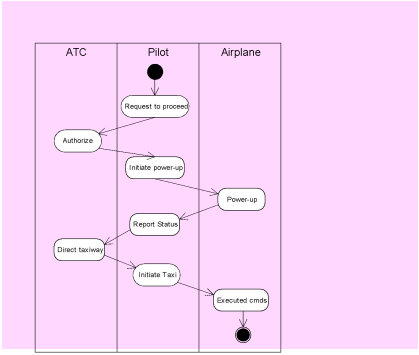
Vision from early 2000s

Present



- Specifications
- Interface requirements
- System design

Future

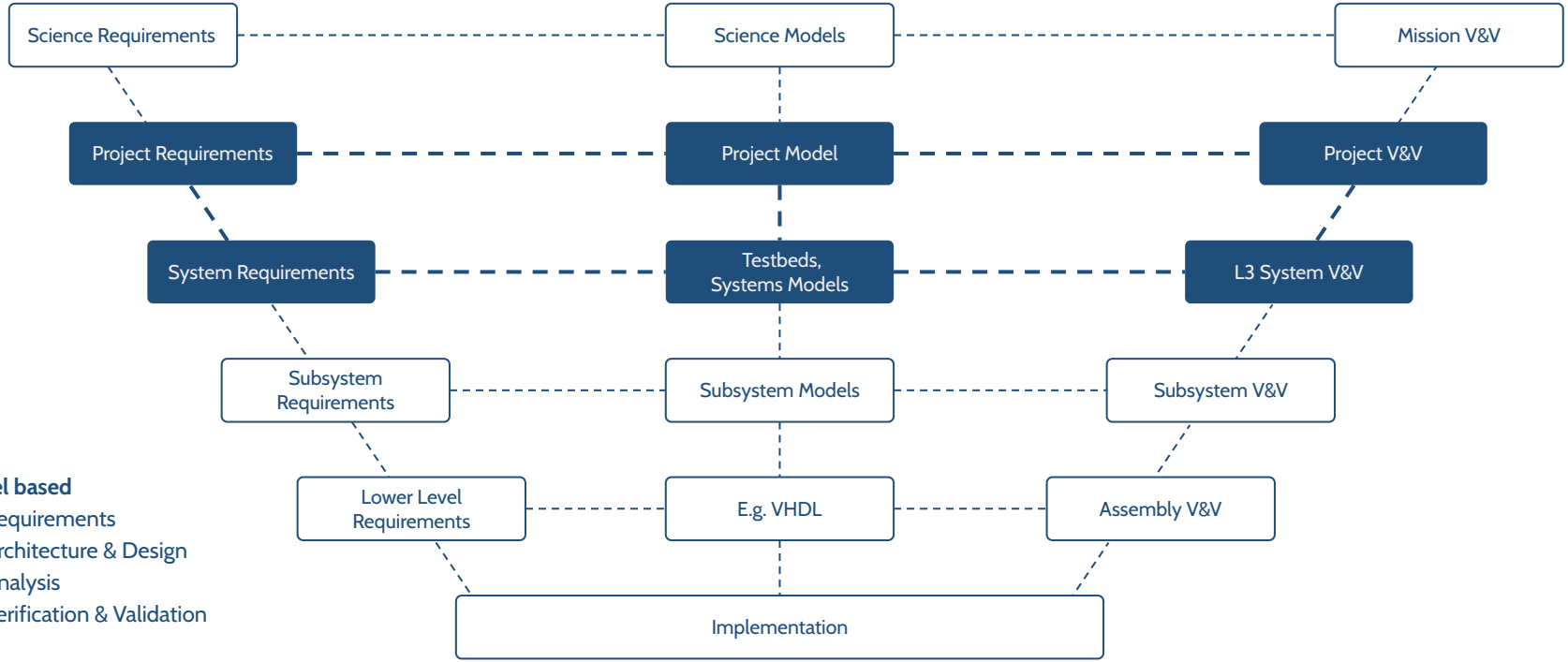


Moving from Document centric to Model centric

“The chains of problem are too weak to be felt until they are too strong to be broken”

Connected information, connected engineers

MBSE along the V-Model



Model based

- Requirements
- Architecture & Design
- Analysis
- Verification & Validation

Topic: Engineers as Humans

Ux Design

Human Challenges

- Cultural Resistance
- Systemic Process Impact
- No Users - The Risk of Failure

Incorporating the Engineers

- Empathy
- Human Centered Design
- Incremental Improvement

JPL Case Study Process

Research

Stakeholder interviews

- Process capture

User Interviews

Roles/Personas

- Needs/Goals
- Workflows
- Use Cases
- Pain Points
- Gaps

Architecture / Requirements

Evaluate current capabilities

Requirements Analysis

- Institutional
- Usability
- Environment
- Operations

Technology Evaluation

Trade study

Heuristic evaluation

Review/ Publish Case Study

Stakeholder review

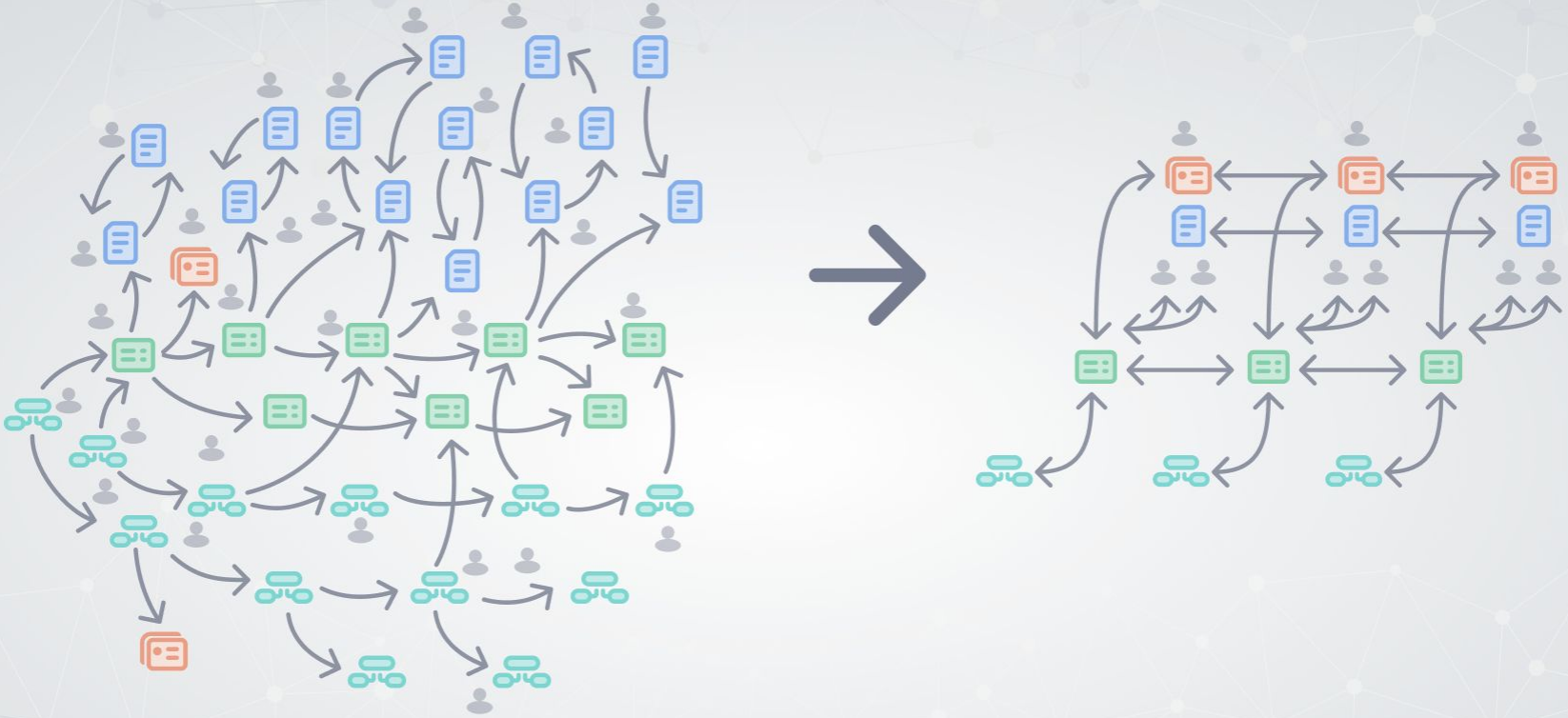
Technology Trades and Evaluations

Solution Architecture

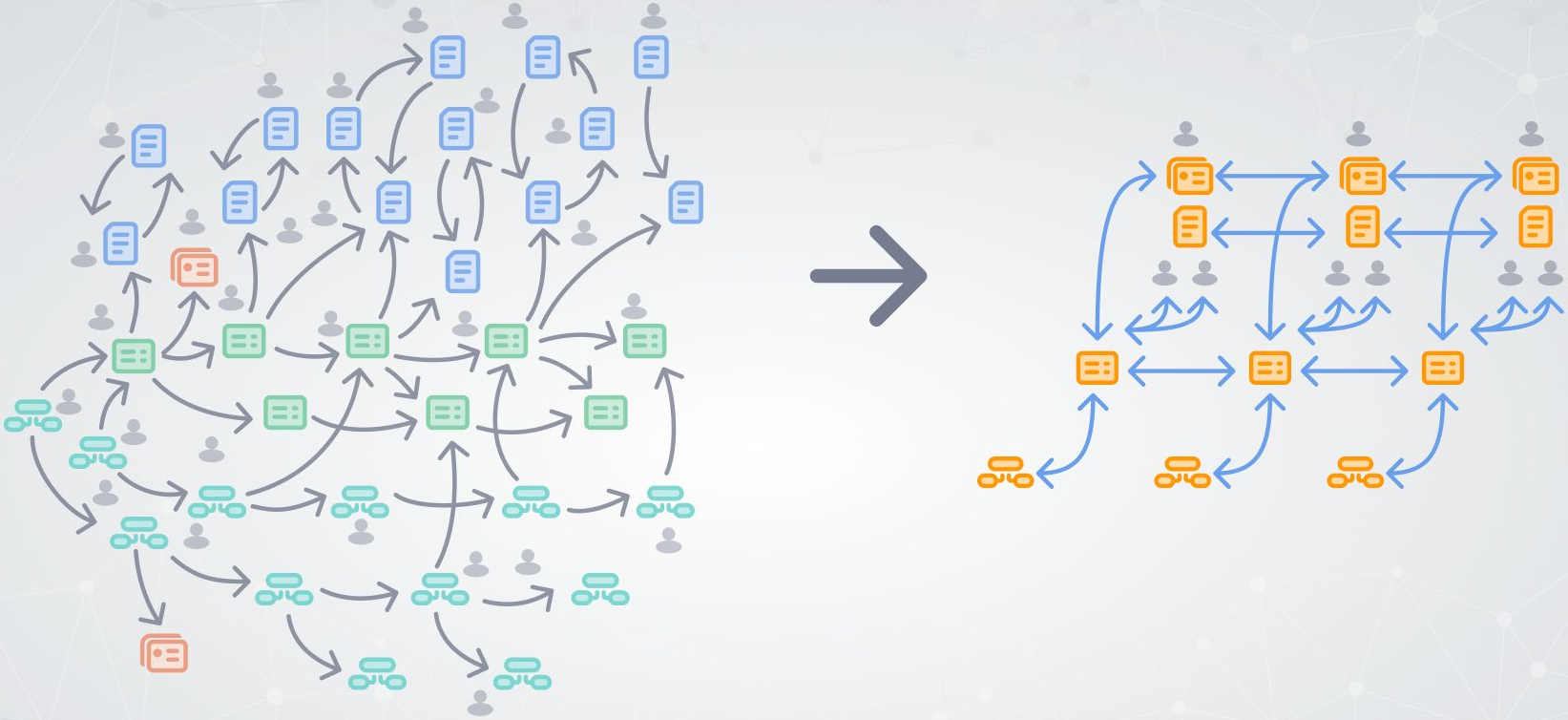
Topic: Technical Strategy

Documents as part of the model

A better way...

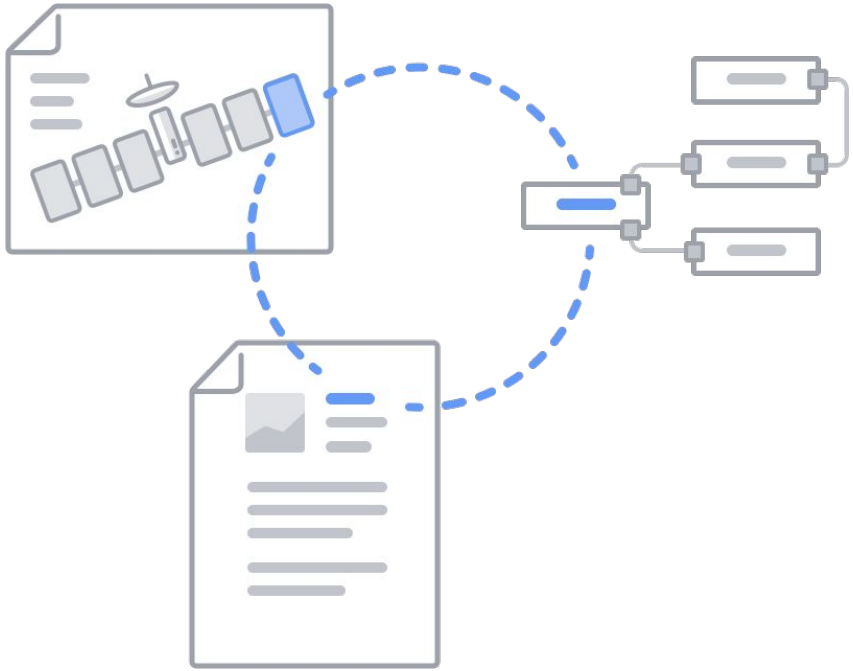


A better way...



Open Model-Based Engineering Environment

- OpenMBEE is a **community** for open source modeling software and models
  - Open source software activities
  - Open source models
  - Open source exchange of ideas
- Participants and adopters:
  JPL, Boeing, Lockheed Martin, OMG, NavAir, Ford, Stevens, Georgia Tech, ESO, ...
- > 400 members



Linked Data Documents with OpenMBEE

Flight Project Impact: Reduction of Overhead

Europa Clipper

100

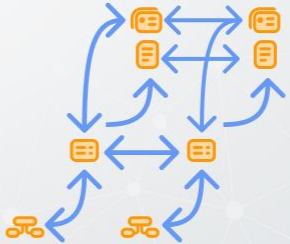
Concurrent users

230+

Documents and decision gate deliverables including

445,000

Connections between elements



Aerospace Industry Impact: Enterprise Scalability

BOEING
Commercial Airplanes

1,000
Concurrent users

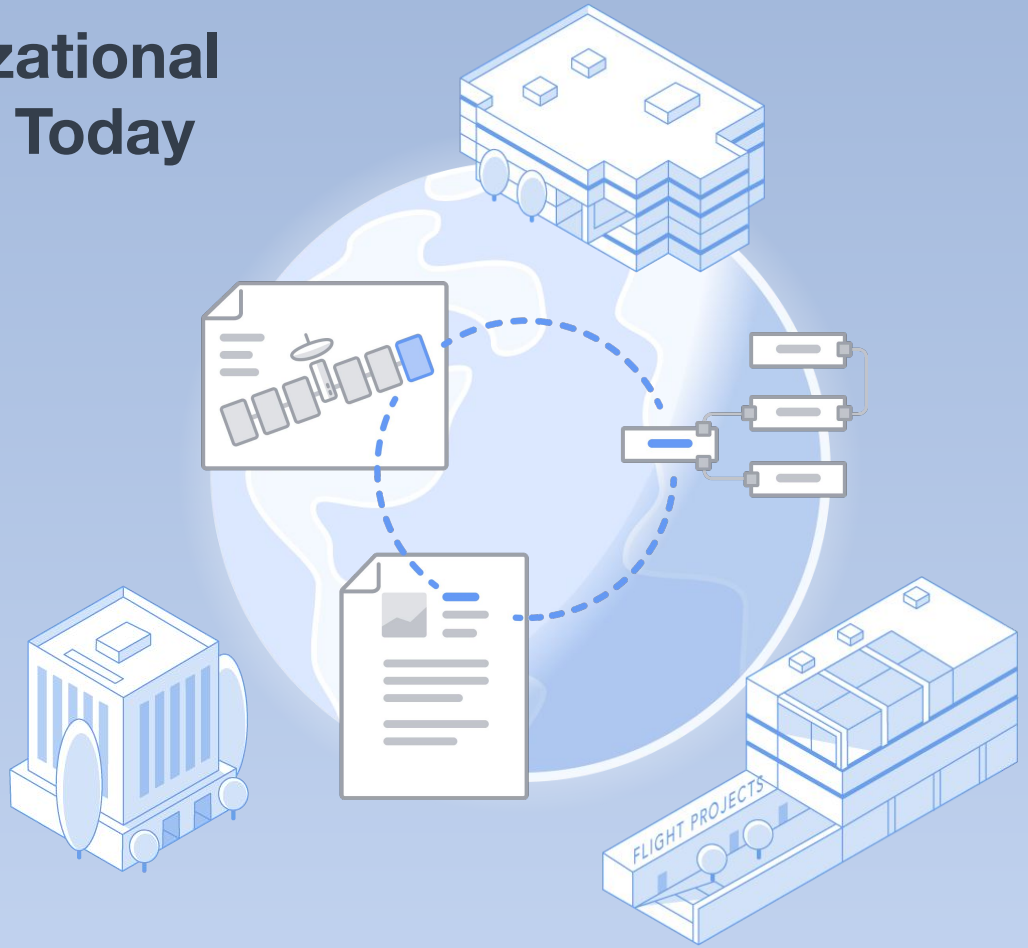
50
Programs

LOCKHEED MARTIN

100
Concurrent users

50
Projects

Intra-Organizational Environment Today



Inter-Organizational Concept

Mars Sample Return Concept

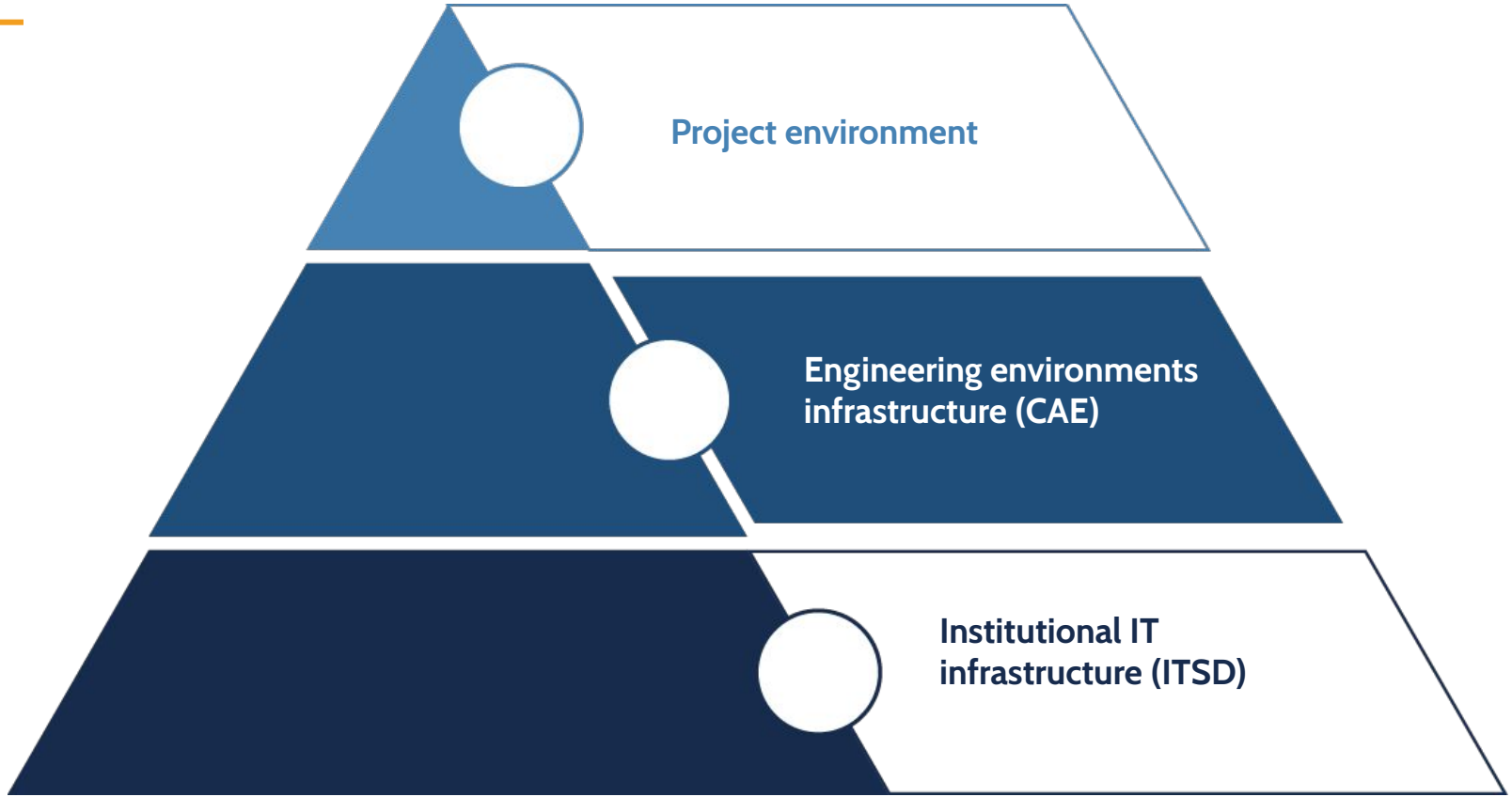
Global Engineering Ecosystem Vision

Connected engineering information for a connected world

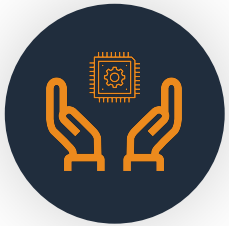
Topic: JPL Engineering Environments

JPL**OpenCAE**

Who We Are


Project environment
Engineering environments infrastructure (CAE)
Institutional IT infrastructure (ITSD)

What We Do



Provide

Get the software you need to help you focus on doing amazing things.

Communicate

Get your questions answered and requests addressed. Reach out to CAE at any time.

Support

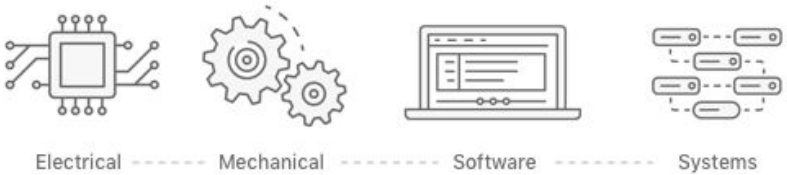
Receive maintenance, upgrades and patches. Your application needs are supported.

Integrate

Use applications that are well integrated and tested. We will make sure they work together.

JPL OpenCAE

Computer Aided Engineering (CAE) supports engineers at JPL by providing and maintaining shared and connected environments of apps and services for engineering.

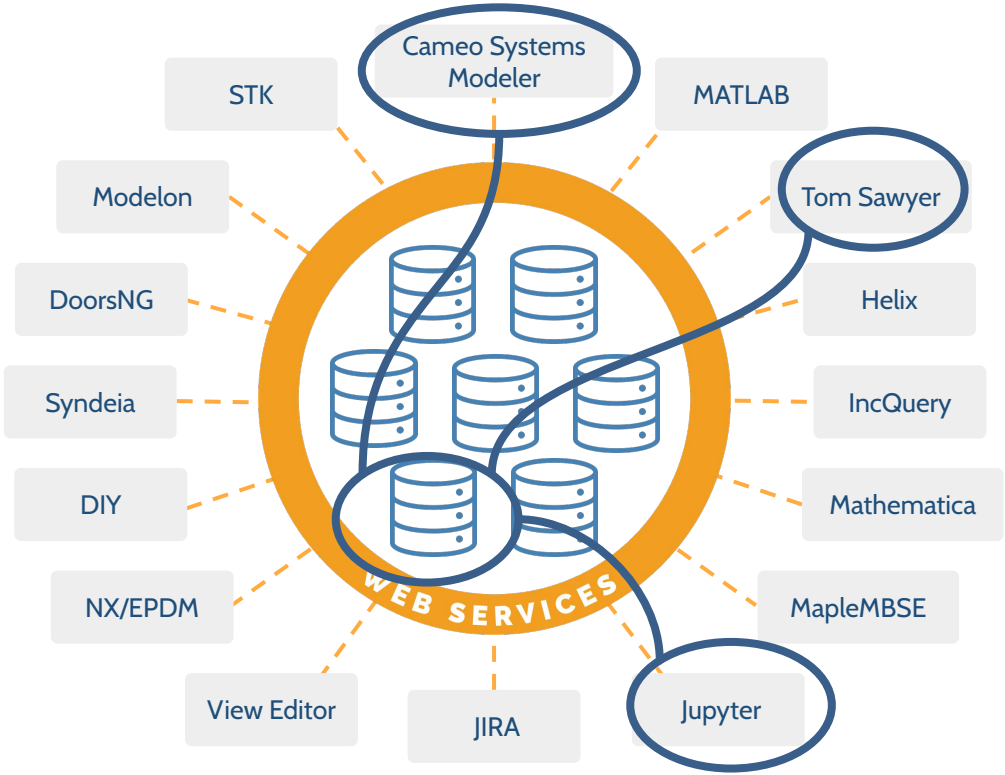


CAE System and Software Environments Connect Engineering Products

Engineering data can be retrieved and used in many engineering products by connecting to the authoritative source of truth

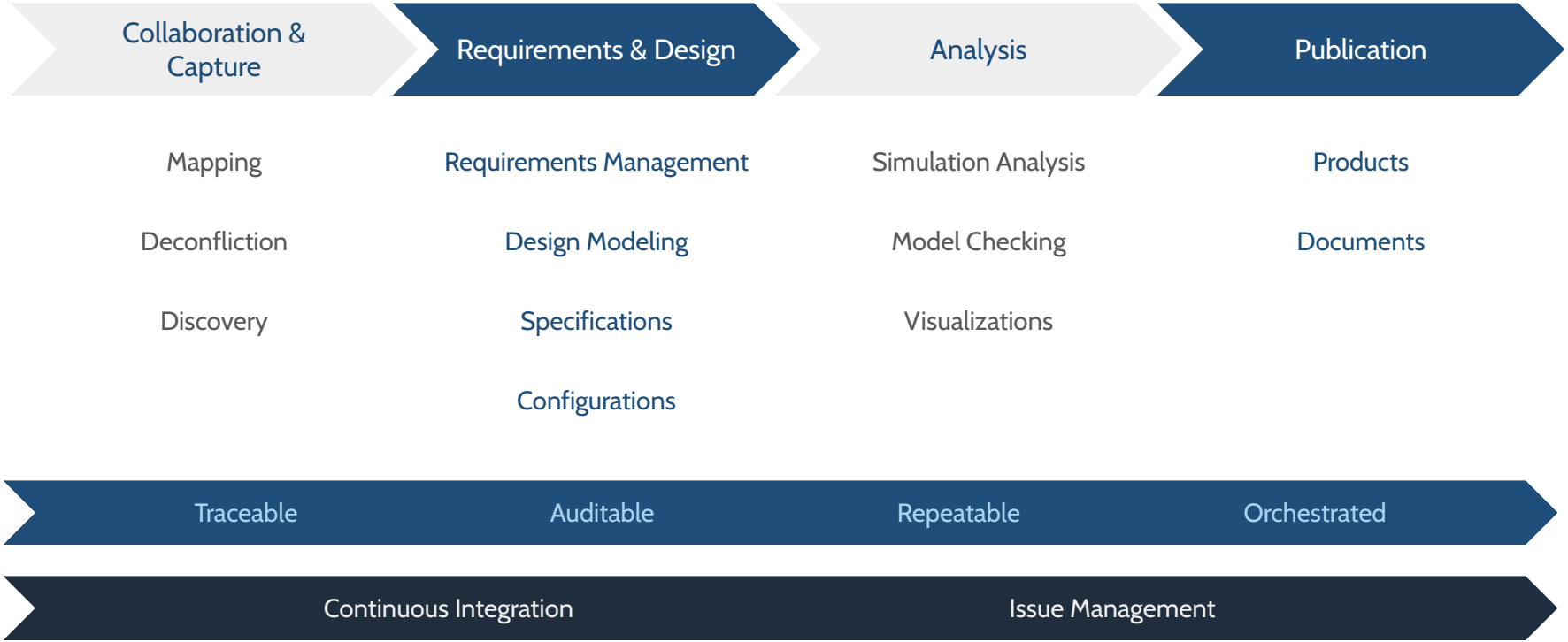
CAE Systems Environment - Architectural Principles

- Multi-paradigm modeling (polyglot) environment
- Best of Breed vs. All-in-One
- Bringing value **to** the user

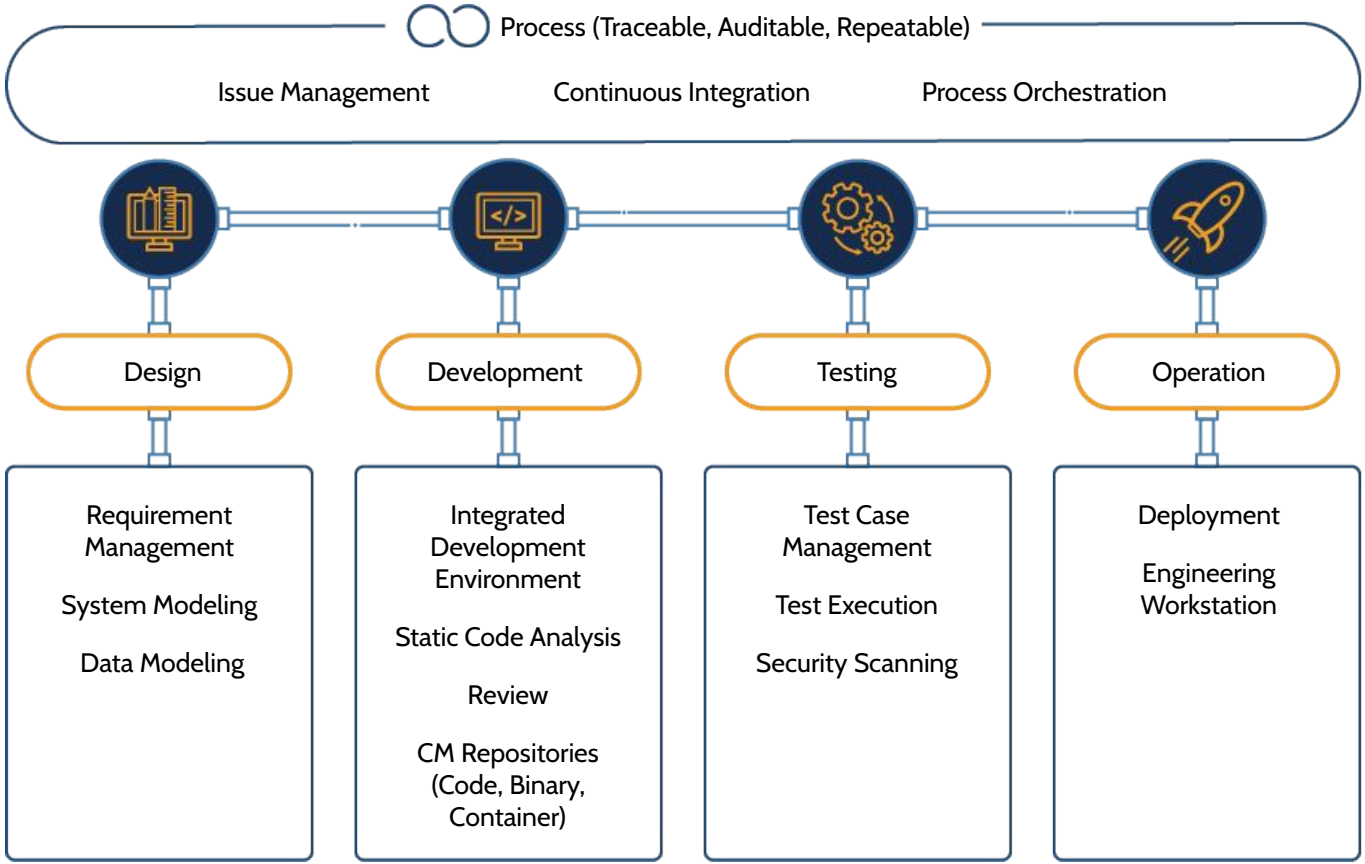


Systems Environment model data repositories are accessible via applications connected through a layer of web services.

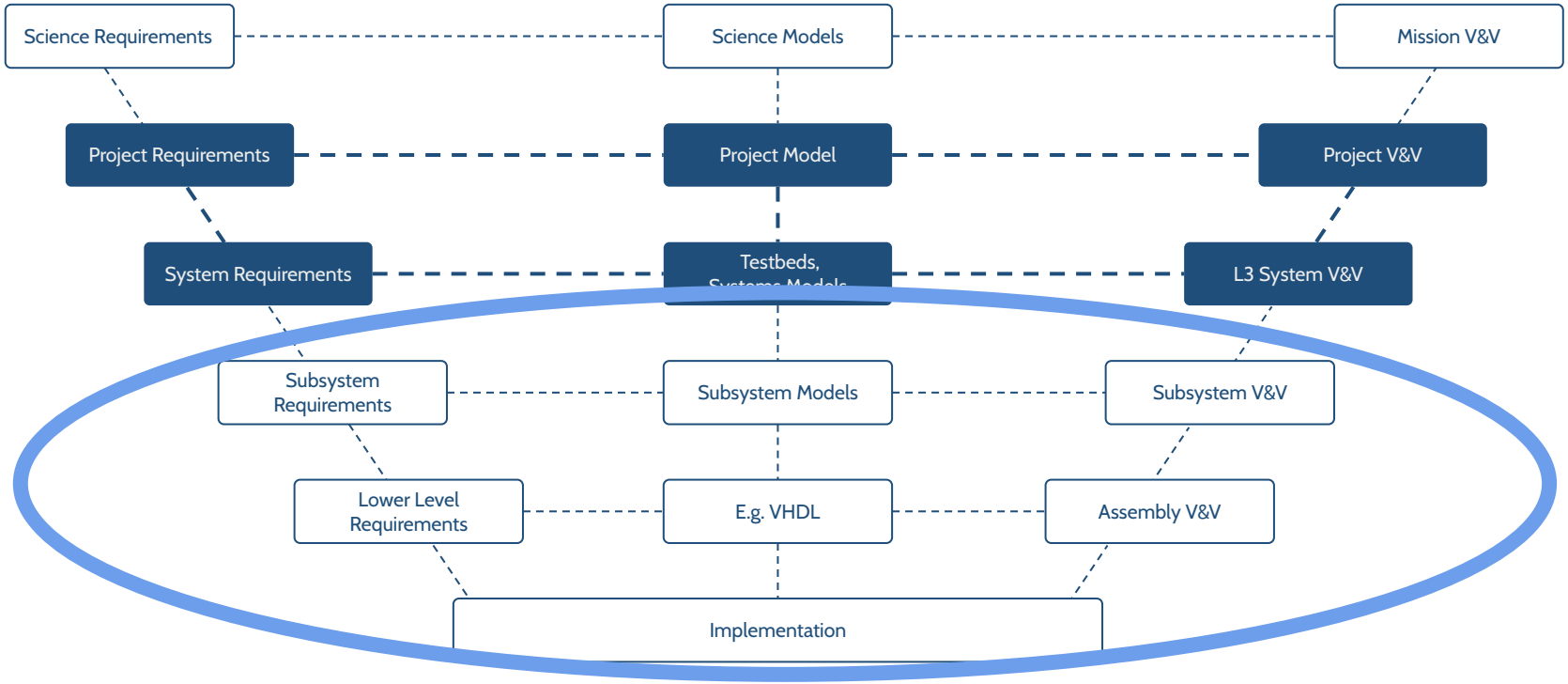
OpenCAE Systems Environment supports a range of capabilities in an Integrated Pipeline:



We offer a Software Environment pipeline



Transition from Systems Engineering to SW Engineering



Topic: Enabling Technology

Bridging SE and people with models and data

SysML v2

jupyter

OpenMBEE

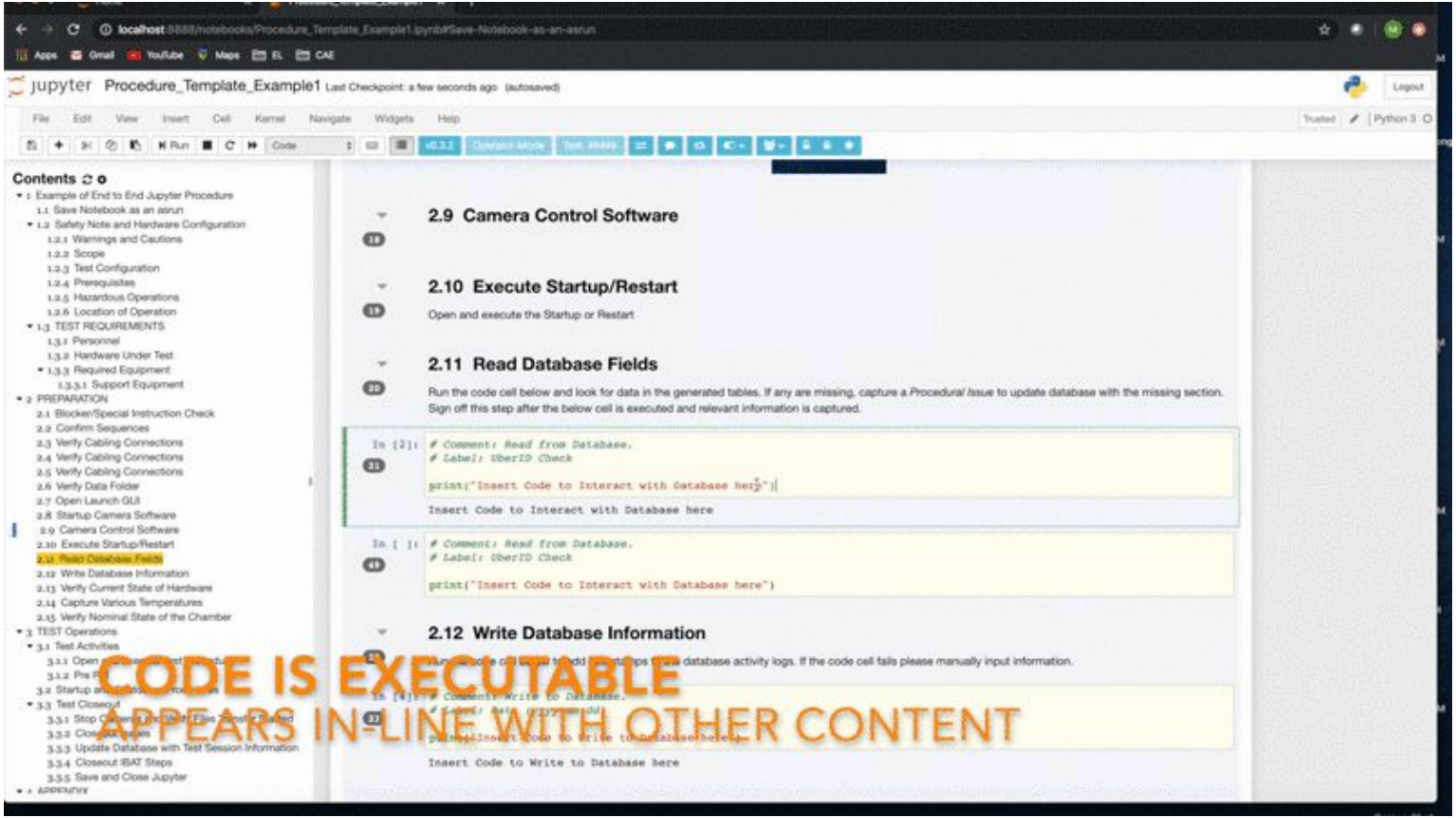
Perseverance Rover's Robotic Arm

Source: https://mars.nasa.gov/mars2020/multimedia/videos/?v=445

Robotic Arm on the Move

Source:

Test Procedures



SysML v2 Key Elements

- New metamodel that is not constrained by UML
  - Grounded in formal semantics
- Robust visualizations based on flexible view & viewpoint specification and execution
  - graphical, tabular, textual
- Standardized API to access the model

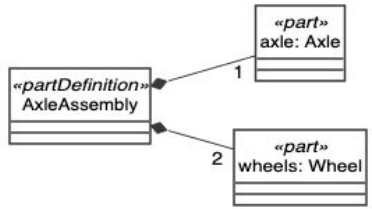
In [1]:

```
1  import ISQ::TorqueValue;
2
3  part def Axle;
4
5  part def Wheel {
6      part lugbolt {
7          attribute torque : TorqueValue;
8      }
9  }
10
11 part def AxleAssembly {
12     part axle : Axle[1];
13     part wheels : Wheel[2];
14
15     connection : Mounting connect axle to wheels;
16 }
17
18 connection def Mounting {
19     end axle: Axle[1];
20     end wheel: Wheel[*];
21 }
22
23 attribute def FuelCmd;
24
25 action def providePower (
26     in fuelCmd : FuelCmd,
27     out wheelTorque : TorqueValue[2]
28 );
29
30 part axle : AxleAssembly;
```

In [2]:

```
1  %viz AxleAssembly --style lr
```

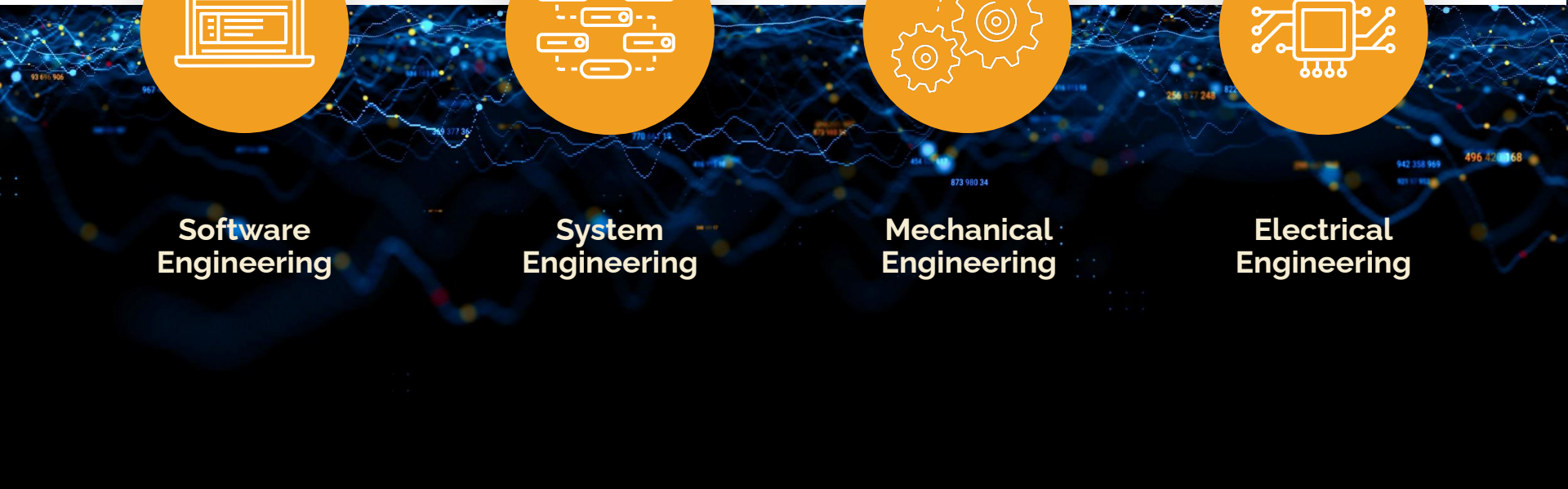
Out[2]:




Questions?

Backup

Who We Serve



Software Engineering

System Engineering

Mechanical Engineering

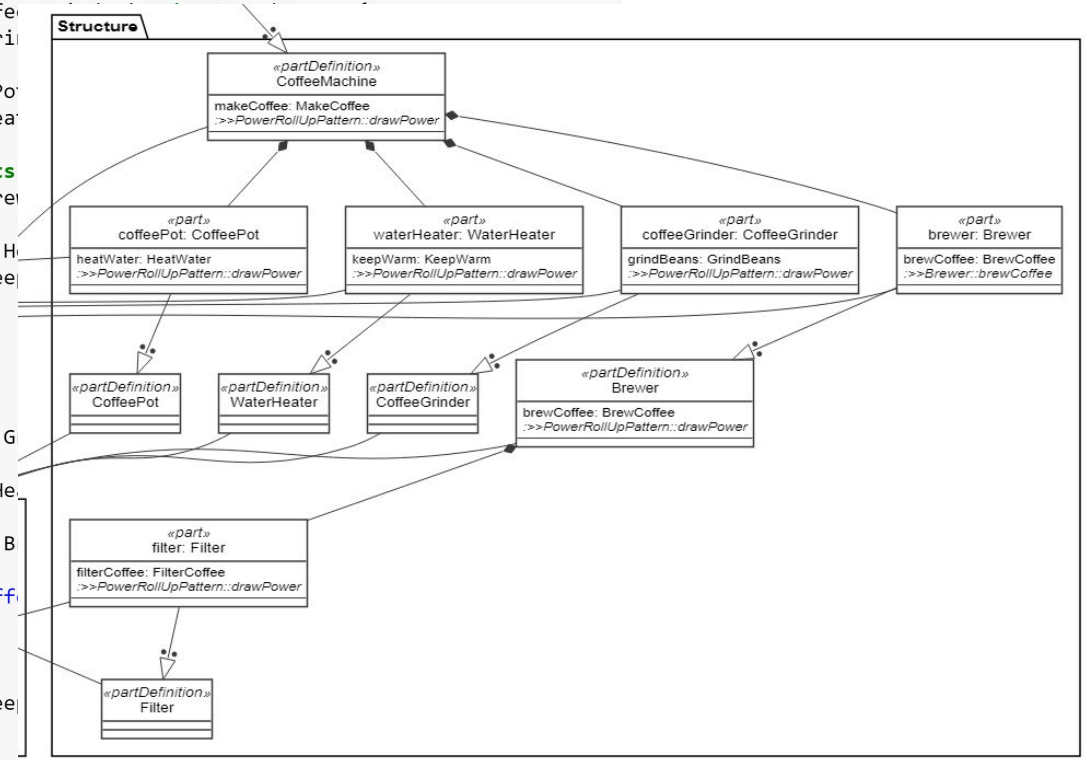
Electrical Engineering

jupyter coffeemachine_rollup_pattern Last Checkpoint: 05/15/2020 (autosaved)

File Edit View Insert Cell Kernel Widgets Help

Run Markdown

```
import ScalarFunctions::sum;


package 'Structure' {
    block 'Coffee Machine'  specializes 'Power Roll-Up Pattern'::'PowerRollUpPattern'{
        part 'coffee Grinder' : 'Coffe
            perform 'Make Coffee'::gri
        }
        part 'coffee Pot' : 'Coffee Po
            perform 'Make Coffee'::hea
        }
        part brewer : 'Brewer' subsets
            perform 'Make Coffee'::bre
        }
        part 'water Heater' : 'Water H
            perform 'Make Coffee'::kee
        }


        activity 'Make Coffee'(){
            first start;
            then action grindBeans : G

            then action heatWater : He

            then action brewCoffee : B
                first start;
                then action filterCoff
                then done;
            }

            then action keepWarm : Kee
            then done;
        }
```

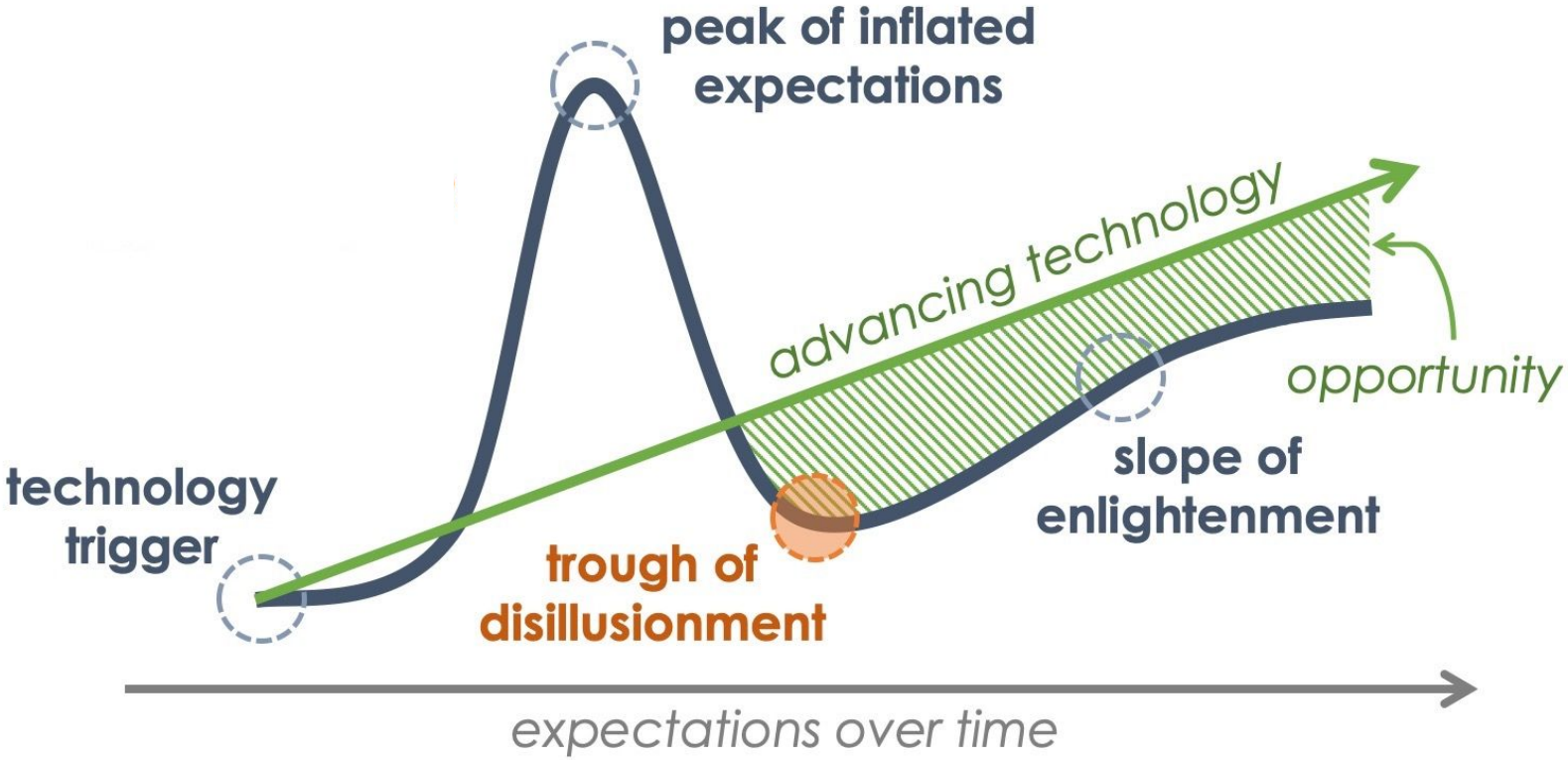


JPL Vision - Dare Mighty Things

- Pursue long-term scientific Quests with a diverse and bold portfolio of missions
- Push the limits of space exploration technology by developing and fielding ever more capable autonomous robotic systems
- Strengthen our core expertise while developing and maintaining strategic partnerships with other NASA centers, U.S. national laboratories, academia, industry, and our international partners
- Build a robust Laboratory of the future that fosters a culture of innovation, openness, and inclusiveness
- Transform our systems to promote easier collaboration and information sharing
- Strengthen our end-to-end mission capabilities and accelerate the infusion of new technologies and capabilities into our future missions
- Inspire the world through our stories and our journey into space
- Support American leadership in space and as we Dare Ever Mightier Things

JPL Vision - Seven Quests

- Understand how Earth works as a system and how it is changing
- Help pave the way for human exploration of space
- Understand how our Solar System formed and how it is evolving
- Understand how life emerged on Earth and possibly elsewhere in our Solar System
- Understand the diversity of planetary systems in our Galaxy
- Understand how the Universe began and how it is evolving
- Use our unique expertise to benefit the nation and planet Earth


peak of inflated expectations
advancing technology
opportunity
technology trigger
slope of enlightenment
trough of disillusionment
expectations over time

The JPL Systems Environment is widely used across

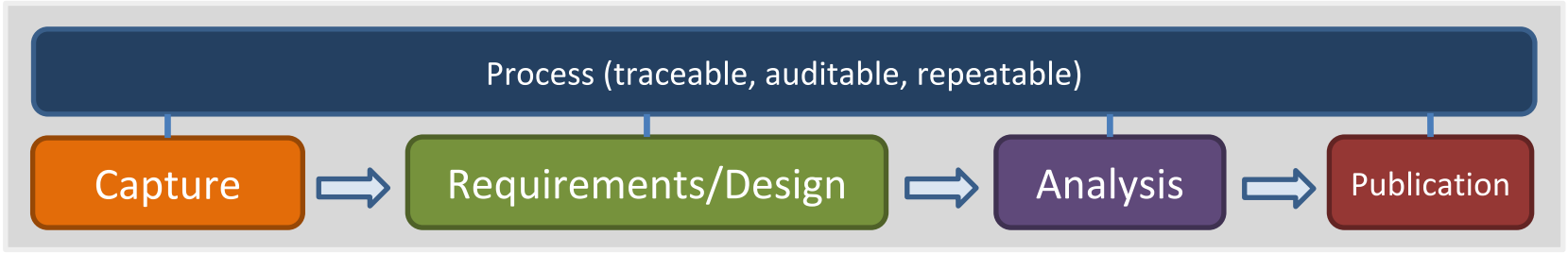
Category	Number	Notes
User engagements	145	TWG, Office hours, Lab-wide talks, trainings
Apps+services	32	Apps & Services
Environment Users	838	TWC users: 100+ Jupyter users 500+ Syndeia users: 40+ Jama: 10+ DNG: 900+
Server projects	192	TWC projects: 227 Syndeia projects: 9 Jama: 5+ DNG: 50
Number of embedded roles	12	
Flight projects	16	
Number of processes	63	
Number of releases	161	

JPL Systems Environment Provides A Wide Range Of Capabilities for the JPL SE Functions

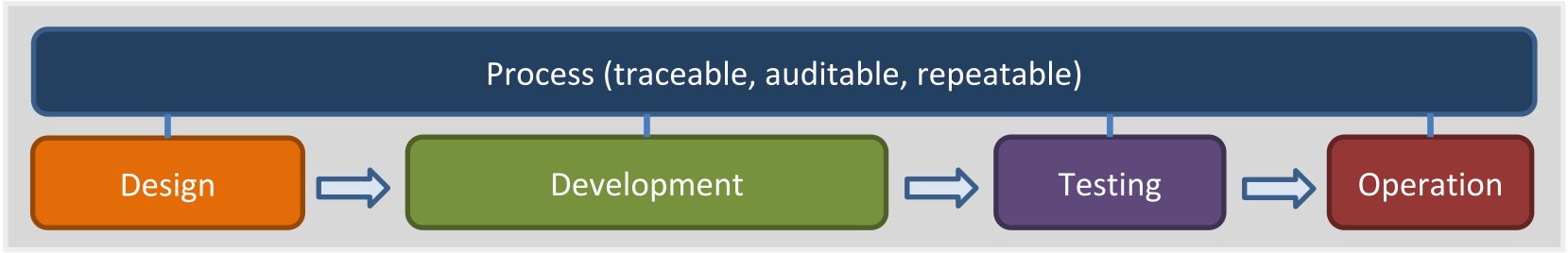
	SE Function	Systems Environment Capability	Systems Environment Tools
1	Architecting	**Collaborative Workspace**, Data Model Design, System Modeling, Fault Protection, Design Communication, Capture Operational Scenarios, System Block Design, Visualize System Architecture	Cameo Systems Modeler, Cameo Concept Modeler, Tom Sawyer
2	Requirements	**Requirements Tracking and Management**, Requirements Design	DNG
3	Analyze and Characterize	**Capture Spacecraft Behavior**, Data Transformation, Large Dataset Analysis, Shared Computing Resources, Process Automation, **Multi-Domain Modeling & Simulation**, System Analysis, Model Checking Flight System and Software Behavior, Analysis Result Distribution	Systems Modeler, Tom Sawyer, Modelica, STK, Maple Workbook, Jupyter, Jenkins, PMA, Cameo Simulation Toolkit
4	Technical Resources	**Subsystem Data Aggregation**, Data Entry, Master Equipment List (MEL), Power Equipment List (PEL)	System Modeler, Maple Workbook, Cameo Simulation Toolkit, STK
5	Interfaces	Design Communication, Systems Integration Testing, Command Dictionary Management	DNG, Cameo Systems Modeler
6	V&V	System Testing, System Integration Testing	DNG, Helix, TestRail
7	Reviews	Collaborative Workspace, Role Capture, Track Model Analytics, Decision Traceability, **Document Generation**, Mission Operation System Coverage Reporting, Data Visualization	Smart Bear Collaborator, View Editor
8	Risk Management	**Connect Requirements to Engineering Artifacts**, Safety and Reliability Analysis	JIRA Risk Plugin
9	Change management	Process Orchestration, Issue Management, Connect Requirements to Engineering Artifacts, System Configuration Management, Analysis Parameter Tracking, Manage Engineering Change Requests	DNG, MMS, TWC, Syndeia, Artifactory
10	Task Planning	Process Orchestration	JIRA, XL Release

Pipelines

Engineering Pipelines



Software Pipelines



JPL Systems Environment Connects silos of information into consistent, traceable, precise engineering documents

OpenMBEE adopters and contributors

NASA

Mars 2020

Europa Clipper

ARRM

Mars Sample Return

MAIA

SWOT

NASA Pathfinder

Europa Lander

Science & Engineering

Thirty Meter Telescope

Japan Aerospace Exploration Agency

Stevens Institute of Technology

Systems Engineering Research Center

Georgia Tech Research Institute

Georgia Tech Aerospace Systems Design Laboratory

Industry

Boeing

Ford Motor Company

Lockheed Martin Corporation

Standards

Object Modeling Group

INCOSE

Vendors

Dassault Systemes

IncQuery Labs

Capella

Intercax

Tom Sawyer

Phoenix Integrations

Maplesoft

OpenMBEE

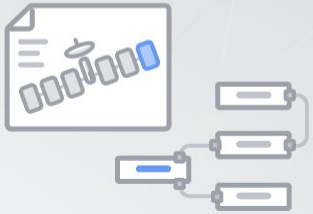
open source initiative

100% JPL
Core Components

TRL 8

Model Management System

View Editor & Platform for Model Analysis



Model Development Kits

Documentation and Training

Thirty Meter Telescope Model

OpenSE Cookbook

OpenMBEE

Thirty Meter Telescope Model

Model Management System

Authoritative Source

OpenSE Cookbook

Model Development Kits

Engineering Modeling

View Editor & Platform for Model Analysis

Document Authoring

Flight Project Impact: Technical Rigor

50

Concurrent users

Mars 2020

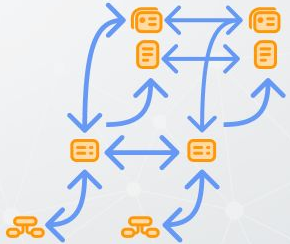
90+

Documents and decision gate deliverables including

- Reference Designator List
- Electrical Function List
- Electrical Functional Block Diagram

180,000

Connections between elements



International Standards Impact: Digital Transformation

OBJECT MANAGEMENT GROUP®

Systems Modeling Language V2

60+ Organizations

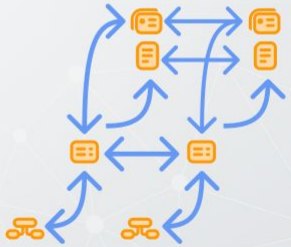
30 Contributors

100+ Consumers

6 Documents including

- SysML v2 RFP
- SysML v2 Submission
- SysML 1.x Specification

10,212 Connections between elements

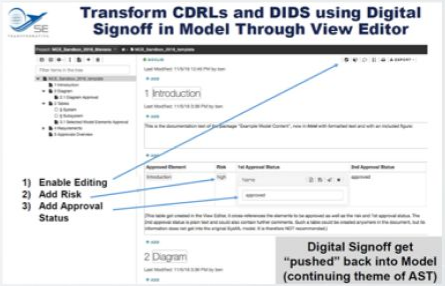


Academia Impact: Inter-Organizational Collaboration

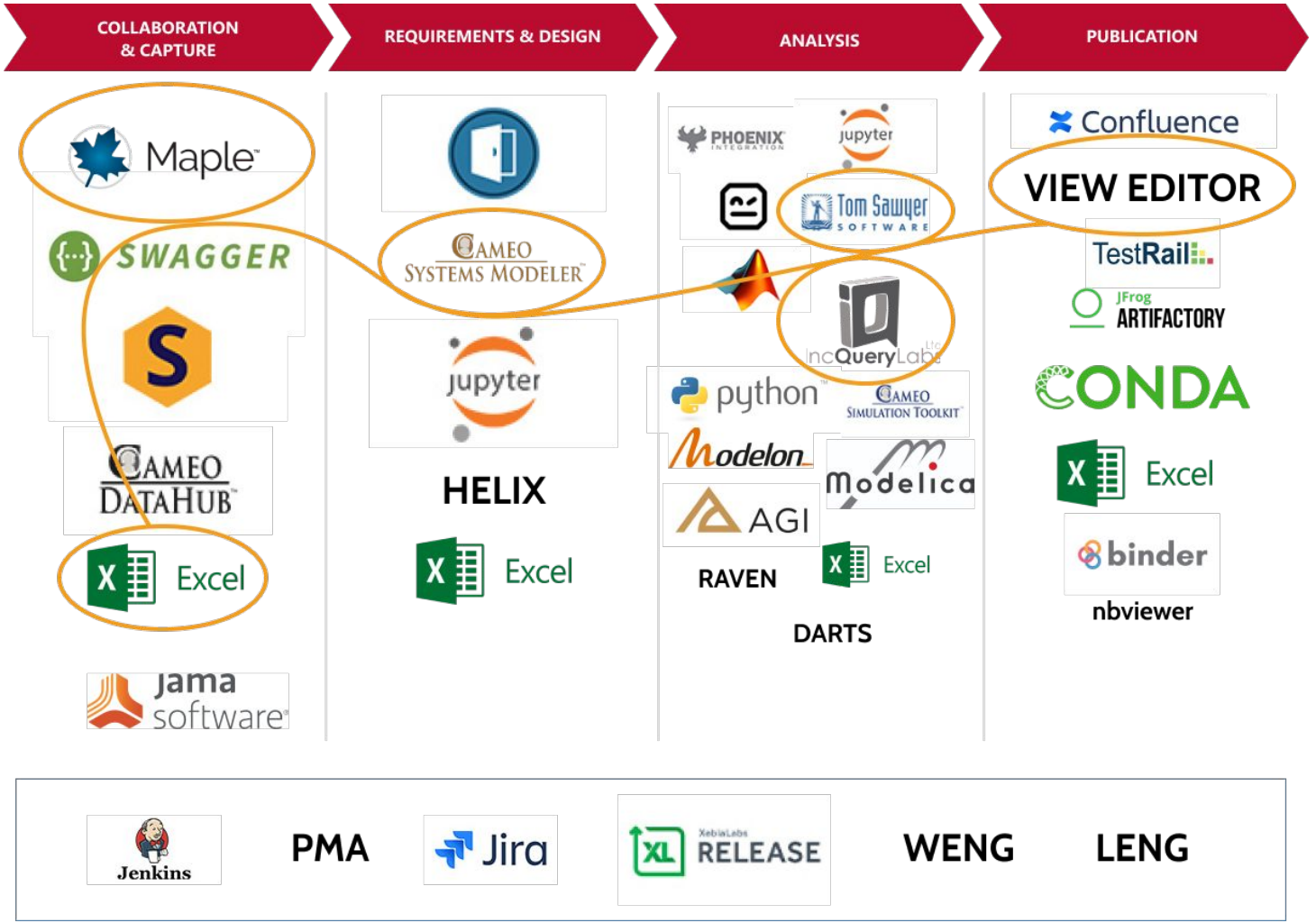
SYSTEMS ENGINEERING RESEARCH CENTER

NAVAIR Model-Based Acquisition Strategy

- Surrogate Pilot RFP delivered to NAVAIR
- Data Item Descriptions (DIDs)
- Contract Data Requirements List (CDRL)



CAE Systems Environment Pipeline



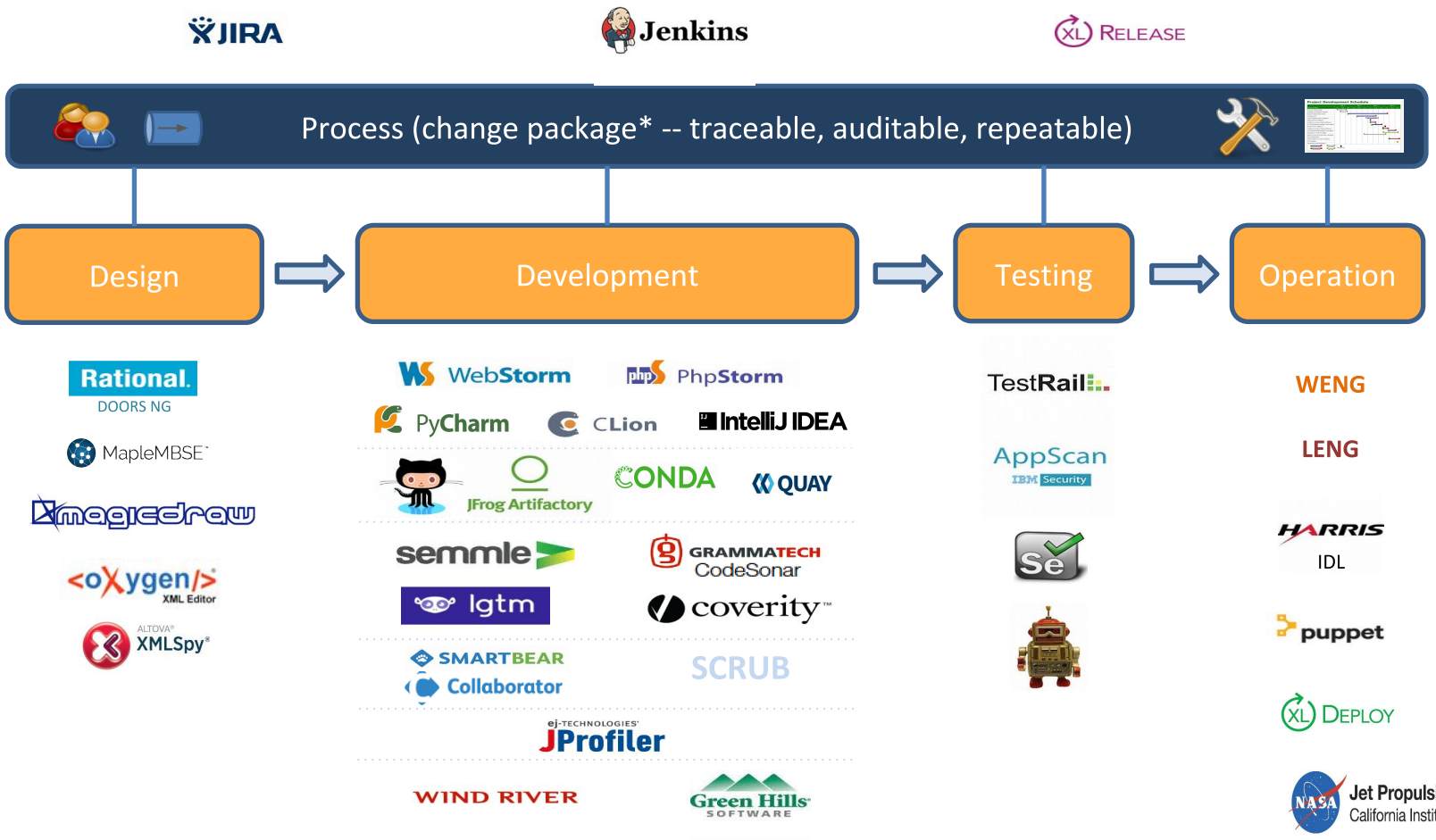
JPL Systems Environment supports various Modeling Languages

Graphical

Hybrid Graphical/Text

Code/Text

Information



Safety-Critical Software Environment

JPL Vision – Seven Quests

- Understand how Earth works as a system and how it is changing
- Help pave the way for human exploration of space
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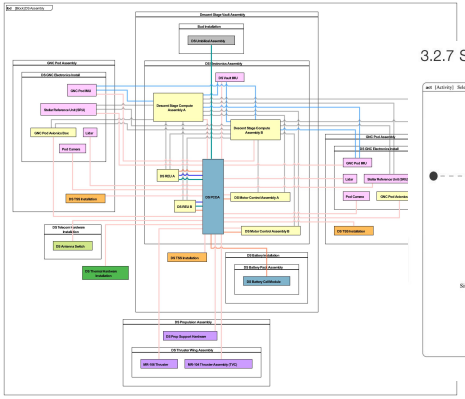
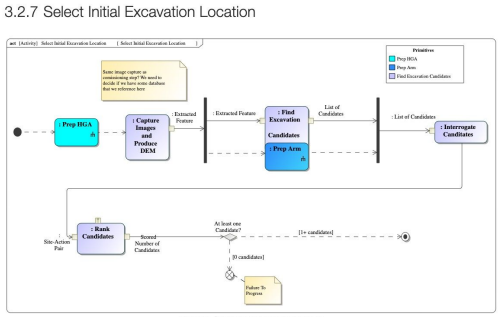
JPL Vision – Dare Mighty Things

- Push the limits of space exploration technology by developing and fielding ever more capable autonomous robotic systems
- Transform our systems to promote easier collaboration and information sharing
- Strengthen our end-to-end mission capabilities and accelerate the infusion of new technologies and capabilities into our future missions

Example: Europa Lander uses Systems Environment

- **Need**:
  - Generate orderly and Compositional System Design, System Block Diagram, PEL, Operational Scenarios from a system model describing the Lander
  - SE products should never be out of sync with the system model
- **Approach**:
  - Leverage Tom Sawyer and MapleMBSE
  - Supply requirements directly from the project to the vendor
  - Coordinate with CAE development team on the use case for Tom Sawyer integration with DocGen and View Editor



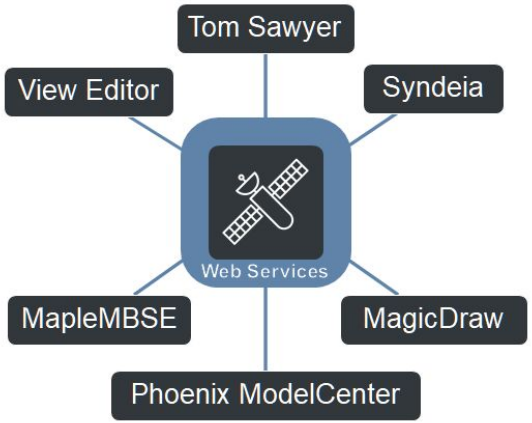


PEL Component	Quantity	Cruise	Pwr (W)	Cruise - SSPA on 75% Time	Pwr (W)	Cruise Occultat
		Mode	CBE	Mode	CBE	Mode
REU-A	1	On	9.5	On	9.5	On
REU-B	1	Off	0	Off	0	Off
Reaction Wheel 1	1	Hold	8.15	Hold	8.15	Hold
Reaction Wheel 2	1	Hold	8.15	Hold	8.15	Hold
				Hold	8.15	Hold
				Off	0	Off
				Hold	8.15	Hold
				Hold	8.15	Hold
				Hold	8.15	Hold

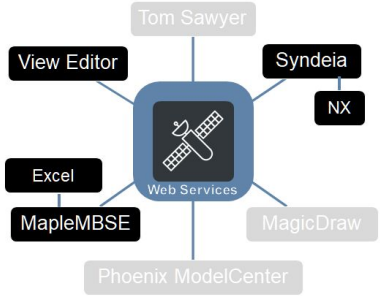
	Level 2	Quanti	Type	Level 3
r Vehicle				
r Vehicle	BIO-BARRIER ASSY	1	BIO-BARRIER ASSY	
r Vehicle	BIO-BARRIER ASSY	1	BIO-BARRIER ASSY	ADAPTER, CRS
r Vehicle	BIO-BARRIER ASSY	1	BIO-BARRIER ASSY	EJCTD, UPR SHELL
r Vehicle	BIO-BARRIER ASSY	1	BIO-BARRIER ASSY	FIXED, LWR SHELL
r Vehicle	BIO-BARRIER ASSY	1	BIO-BARRIER ASSY	FIXED, UPR SHELL
r Vehicle	BIO-BARRIER ASSY	1	BIO-BARRIER ASSY	FSTNRS
r Vehicle	BIO-BARRIER ASSY	1	BIO-BARRIER ASSY	MRMN CLAMP INSTL
r Vehicle	DOV ASSY	1	DOV ASSY	
r Vehicle	DOV ASSY	1	DOV ASSY	3/8"FSTNRS, SEP NUT
r Vehicle	DOV ASSY	1	DOV ASSY	CUP, CATCH (ON DOS
r Vehicle	DOV ASSY	1	DOV ASSY	DOS ASSY
r Vehicle	DOV ASSY	1	DOV ASSY	DOS ASSY
Europa Lander Vehicle	DOV ASSY	1	DOV ASSY	DOS ASSY

Europa Lander Environment Adaptation Examples

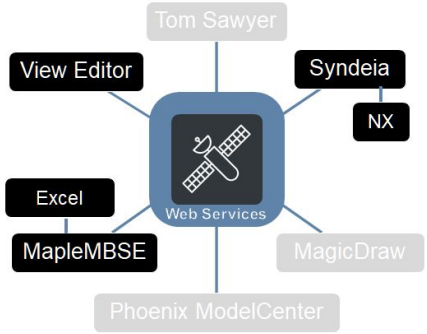
Selected Subset



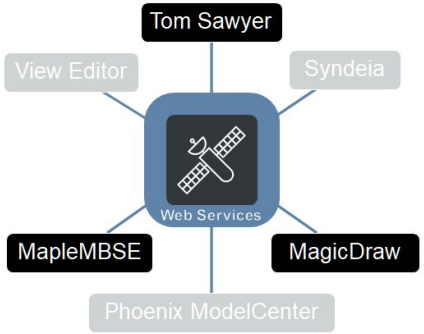
Compositional System Design



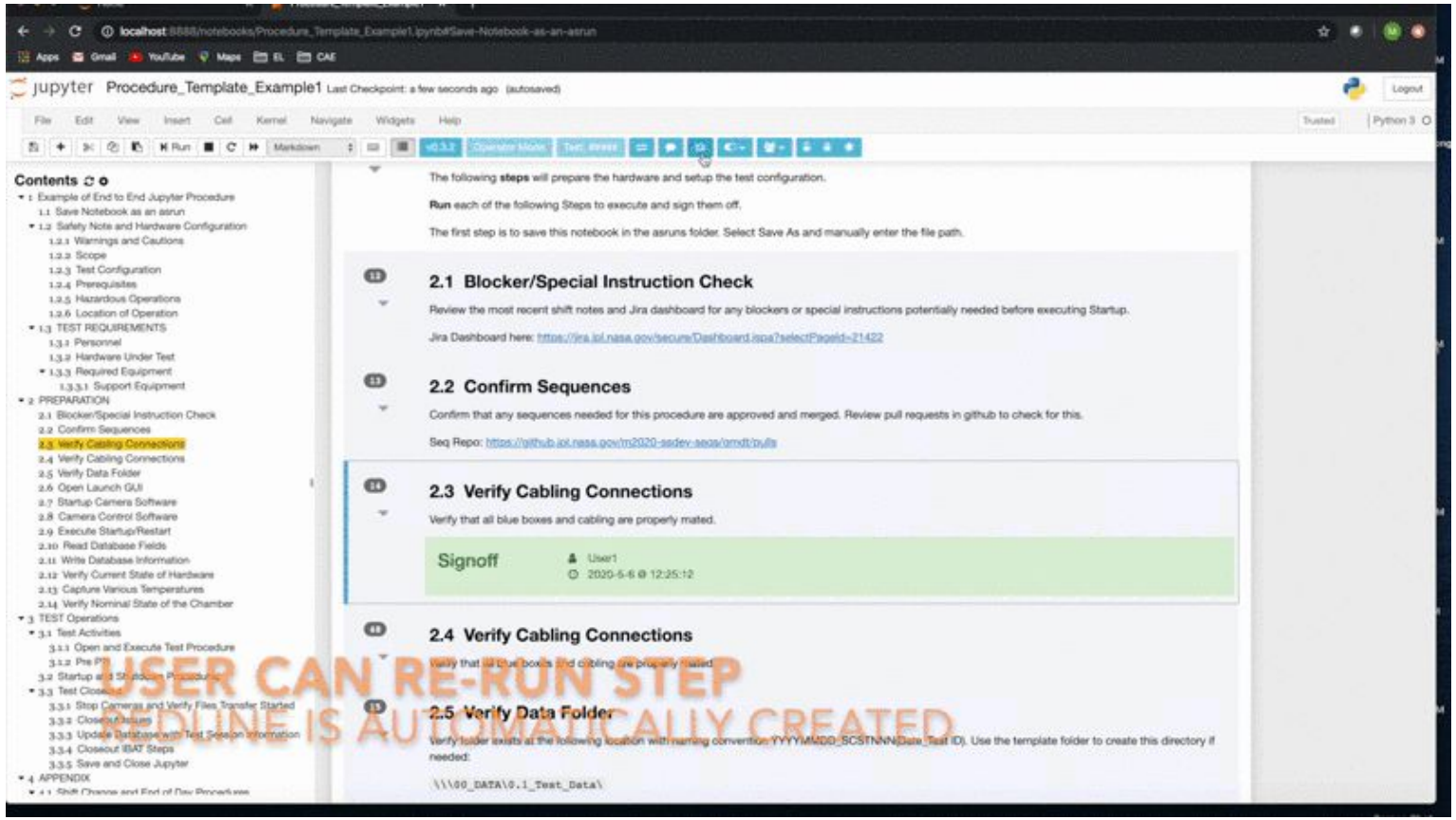
Master Equipment List



System Block Diagram



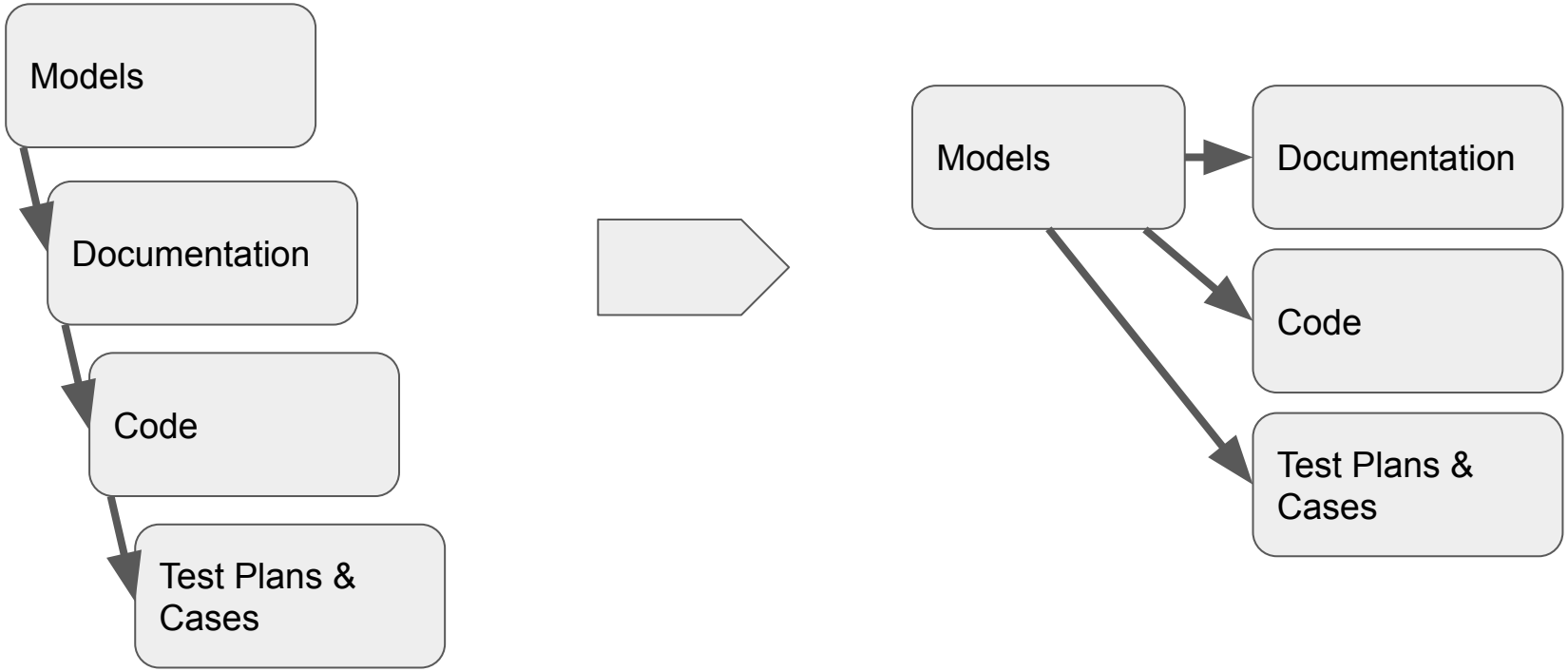
Test Procedures



Thermal Vacuum (TVAC) Testing

Source: https://www.nasa.gov/feature/jpl/nasas-mars-2020-gets-a-dose-of-space-here-on-earth

Model Driven instead of Document Driven for System to Software



Engineering Workstations

- **Applications**
  - **LENG**
  - **WENG**
- Cloud engineering Linux and Windows workstations that can be accessible in JPL network.

LENG and WENG

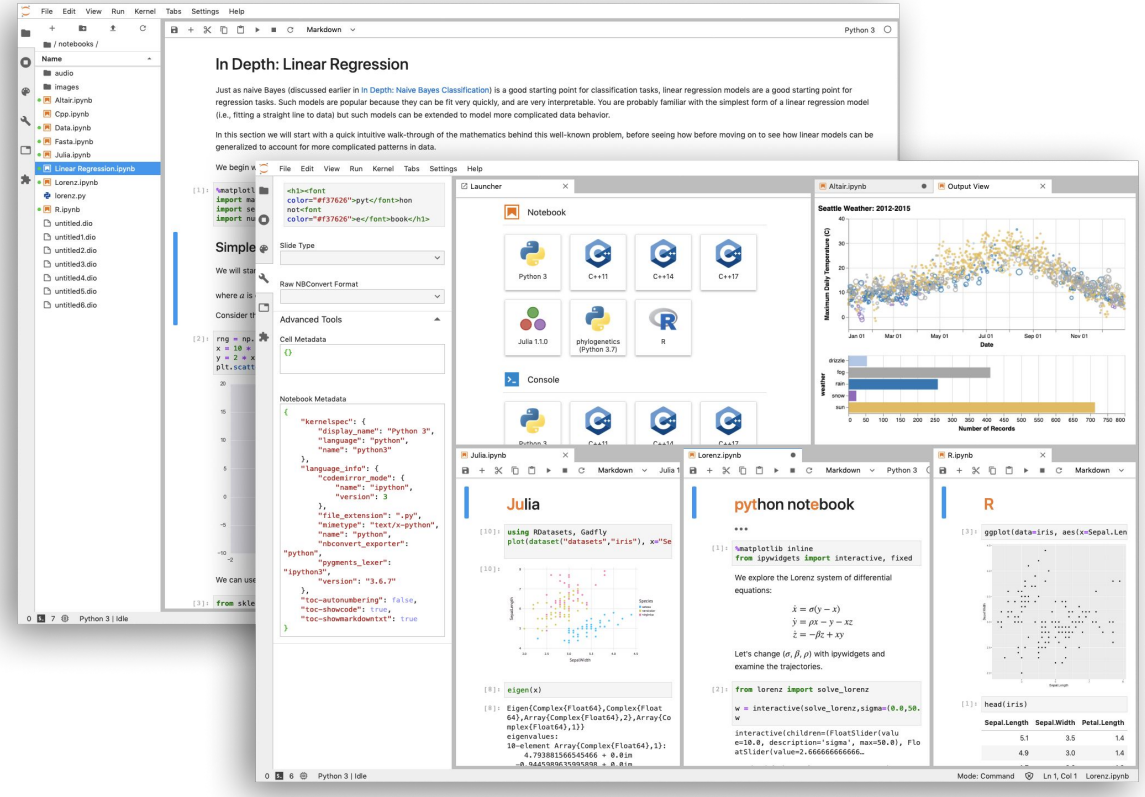
What can I do with Jupyter?

- Capture entire computing process
- Develop and execute code in a variety of languages
- Document and communicate results in-line with code
- Connect Models and Data

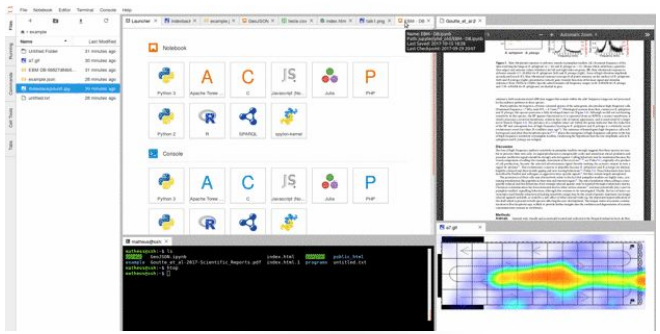
What is JupyterLab?

Interactive, exploratory, browser-based computing environment for:

- engineering
- data science
- scientific computing
- ML/AI
- and so much more...



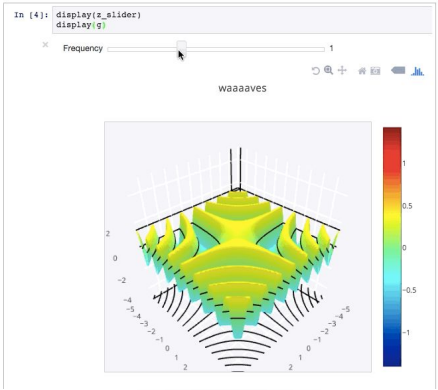
JupyterLab Features



Rich engineering narrative

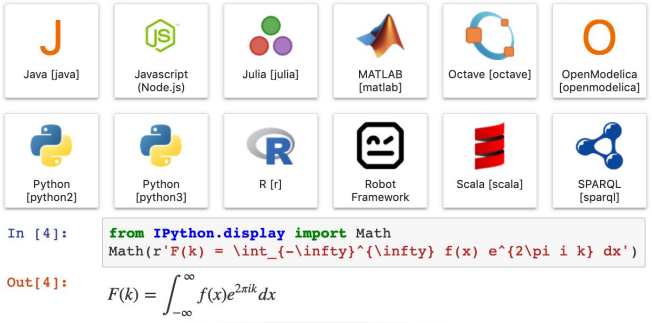
Feature rich and integrated computational environment

Notebooks as reproducible and executable reports



Interactive & visual

Live code, narrative text, equations (LaTeX), images, visualizations, audio, video, widgets



Widely popular & supported

~100 programming languages supported

Millions of public notebooks on GitHub to find inspiration

SysML v2 Submission Team

- A broad team of end users, vendors, academics, and government liaisons
  - Currently over **160** members from **71** organizations
- Driven by RFP requirements and user needs
- Developing submissions to both SysML v2 language and API RFPs

The SysML v2 Submission Team after a productive week collaborating on the specification at the OMG Technical Meeting, Long Beach. (Dec 2019)

SysML v2 API and Services

SysML v2 API and Services 1.0.0

/assets/swagger/openapi.yaml

REST/HTTP binding (PSM) for the SysML v2 standard API.

Project

Commit

Element

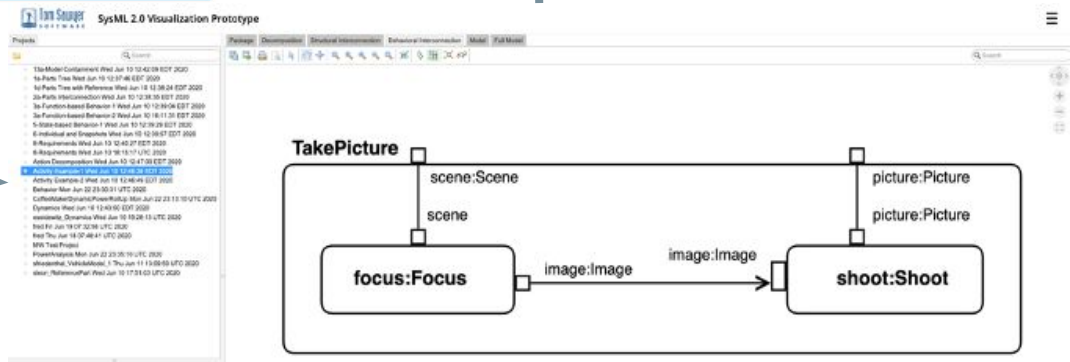
GET	`/projects/{projectId}/commits/{commitId}/elements`	Get elements by project and commit
GET	`/projects/{projectId}/commits/{commitId}/elements/{elementId}`	Get element by project, commit and ID
GET	`/projects/{projectId}/commits/{commitId}/roots`	Get root elements by project and commit

Relationship

GET	`/projects/{projectId}/commits/{commitId}/elements/{relatedElementId}/relationships`	Get relationships by project, commit, and related element.

leverages

enables



OpenMBEE Updates

- New home with NumFOCUS
- First *International* Workshop on OpenMBEE at MODELS 2020 on October 19, 2020
  Register @ https://www.openmbee.org/models2020
- Architecture in development simplifies software operations while adding new capabilities

OpenMBEE is now a NumFOCUS Sponsored Project

OpenMBEE Vision

- Unlock value through commoditization
  - Open / Inner source
  - Discoverable
  - Searchable
  - Learnable
- Provide a standards powered engineering platform using SysML v2 + API & Services

OpenMBEE Vision

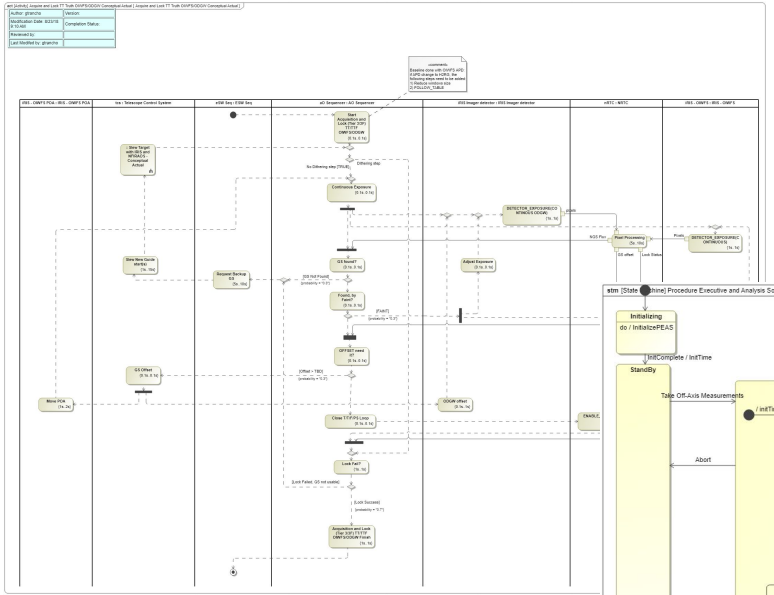
- Marry the ubiquity and popularity of programming languages, e.g. Python, with the rigor and durability of systems modeling
- Augment Jupyter's multi-language analysis capabilities with modeling and connected engineering

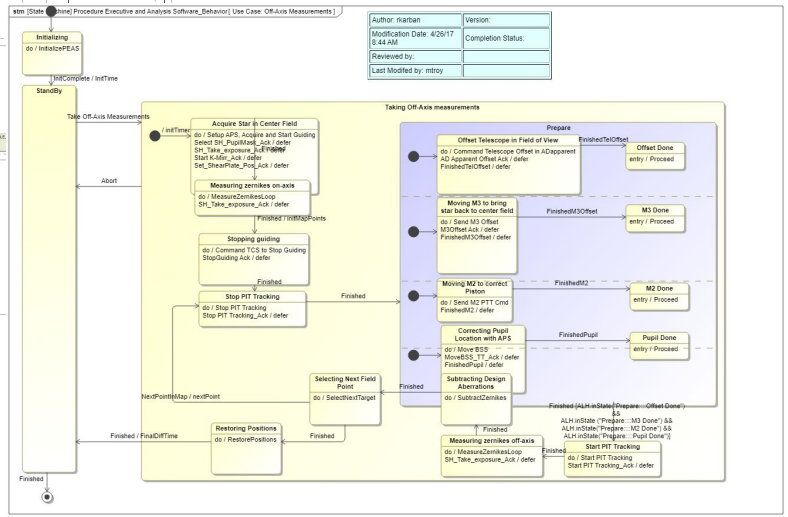
OpenMBEE Vision

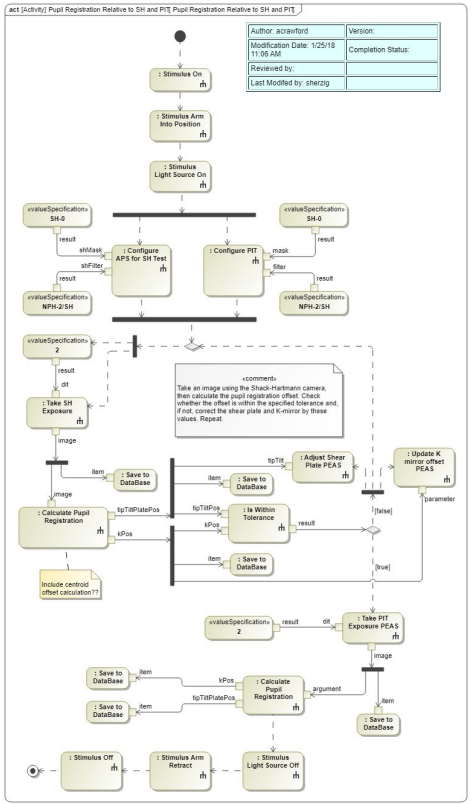
- Enable novel data-driven analyses with advanced capabilities, as a service
  - graph querying
  - distributed computing
  - real time collaboration

Join the community in making this vision into a reality @ openmbee.org

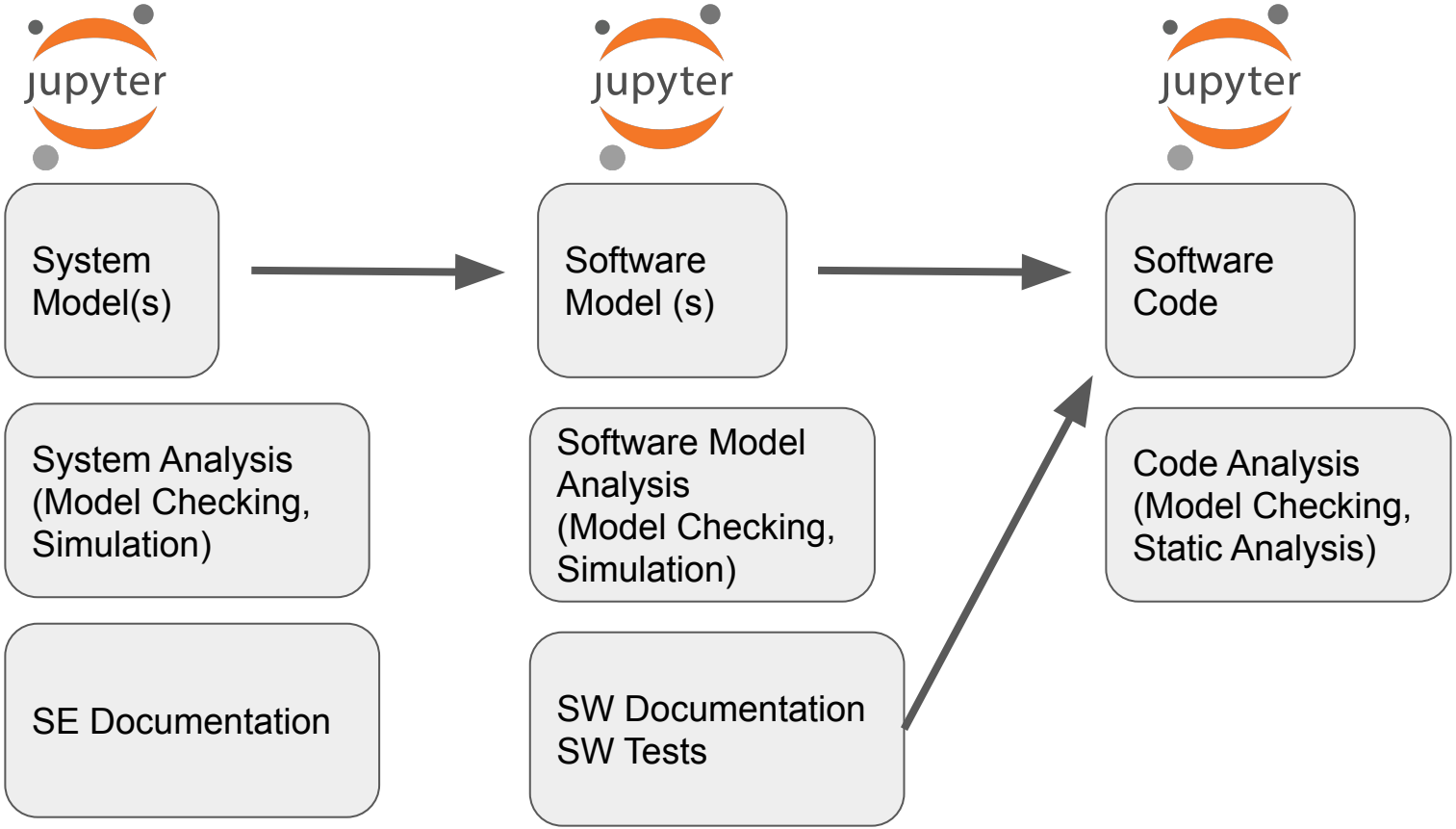
Thirty Meter Telescope Digital Twin - Behavior modeling for executability and auto-coding







Semantic consistency across life-cycle and tool-chain



Evolving Cloud Compute Services for Systems and Software

- 200+ servers in the cloud
- 1,000+ volumes totaling 170+ TB
- 1000+ users
- 20 supported flight projects
- 60 apps and services
- Full Test String - Test, Integration, User Acceptance, Production
- Managed Services
- Software as a Service

The Line in partnership with CAE offers project and domain specific adaptations

- CAE provides the same environment to all its customers (engineers and scientists)
- Embedded roles work directly on projects to adapt the standard environment specific to the project goals or methodology
- This includes but is not limited to:
  - Project specific integrations
  - Project specific configurations
  - Project specific customizations
- Embedded roles capture user needs in general case studies which inform the CAE architecture
- This has been demonstrated for example on M2020, Europa Lander, Europa Clipper, Psyche, Mars Sample Return, Thirty Meter Telescope

Engage the User Community through the Technical Working Groups TWGs

- Technical Working Groups are a **forum for practitioners concerns**
  Projects and line stakeholders, vendors
- For Engineering **Environment** and **key tools**
- Participate in identifying **use cases, workflows, issues, and roadmaps**
- Regular meetings **engaging stakeholders** and **vendors**

OpenMBEE

Thirty Meter Telescope Model

Model Management System

Authoritative Source

OpenSE Cookbook

Model Development Kits

Engineering Modeling

View Editor & Platform for Model Analysis

Document Authoring

Integration and change package