NEPP ETW 2017

Reliability Assurance of CubeSats using Bayesian Nets and Radiation-Induced Fault Propagation Models

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This work supported by NEPP and the NASA Reliability and Maintainability Program under Grant and Cooperative Agreement Number NNX16AR25G

NEPP - Small Mission Efforts

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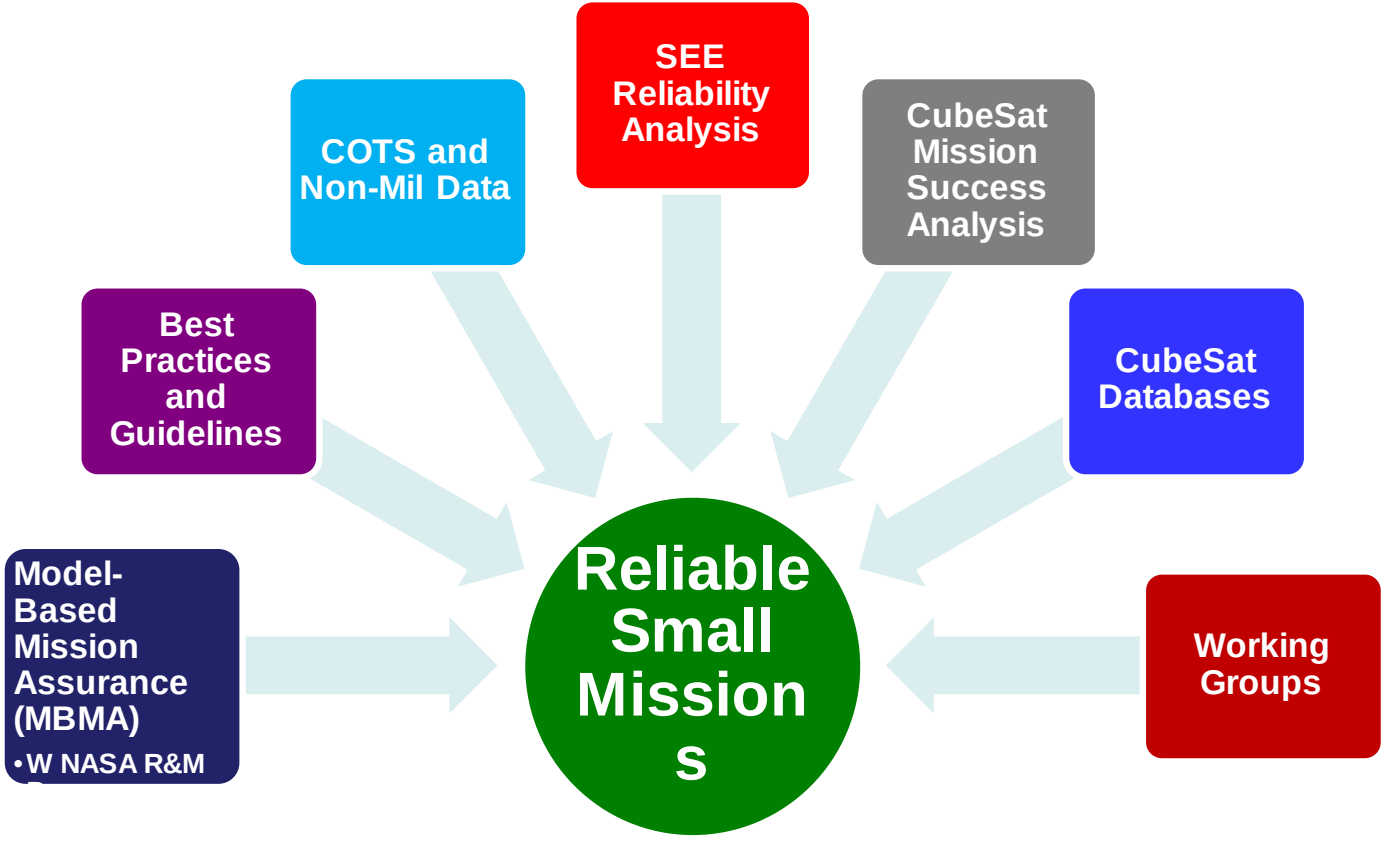

Integrated System Design for Radiation Environments

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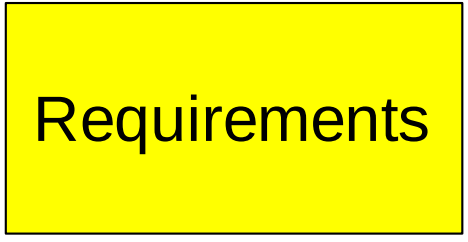

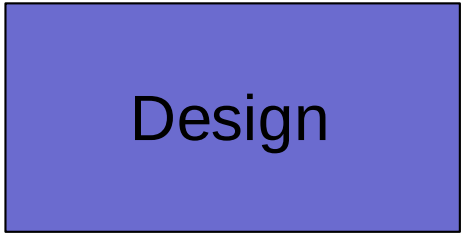

Integrated System Design for Radiation Environments

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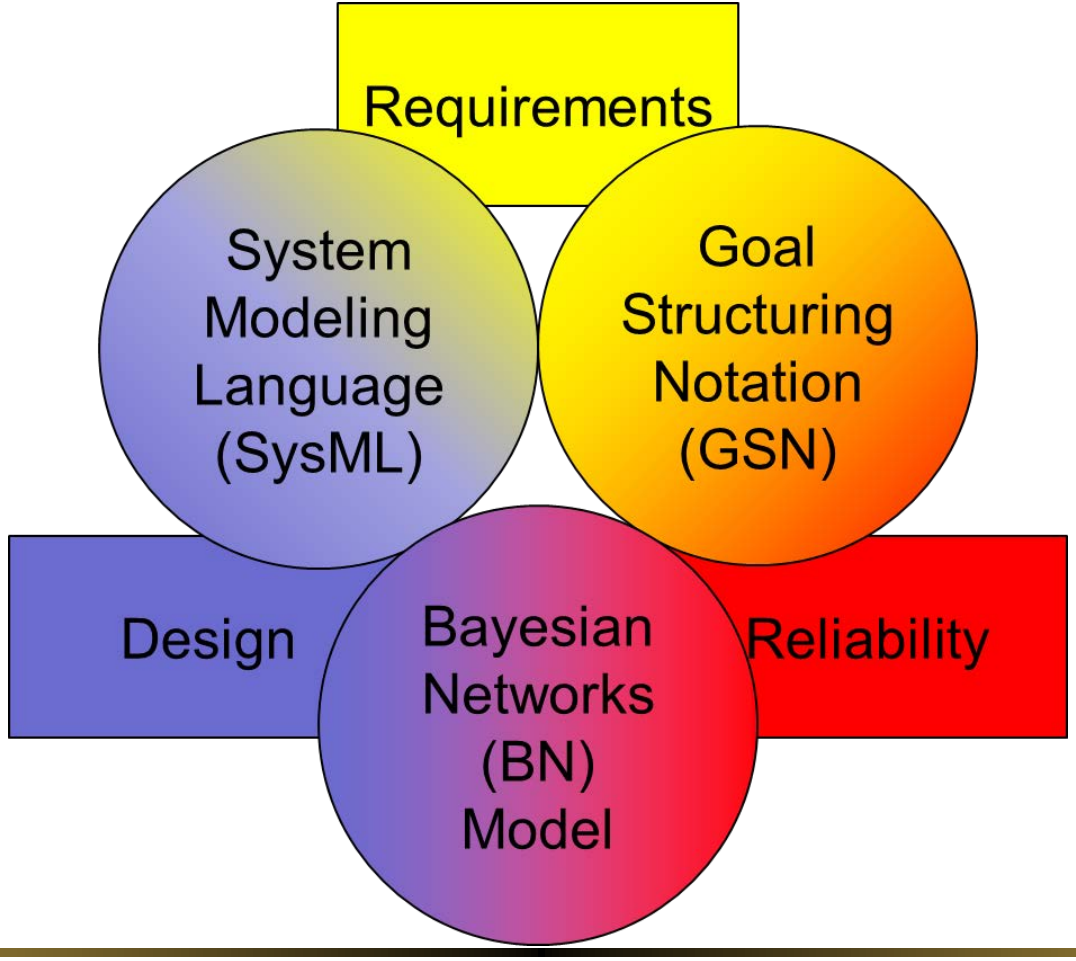

Integrated System Design for Radiation Environments

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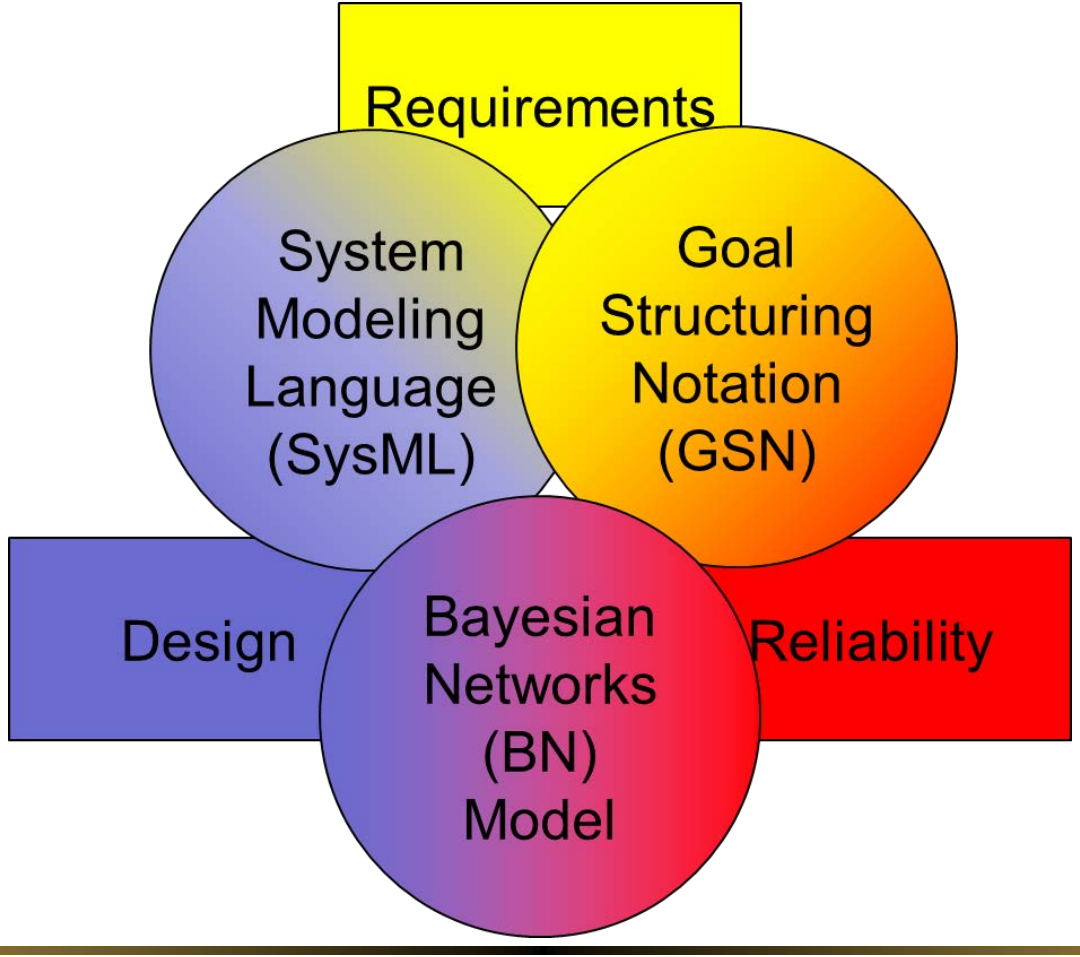

Integrated System Design for Radiation Environments

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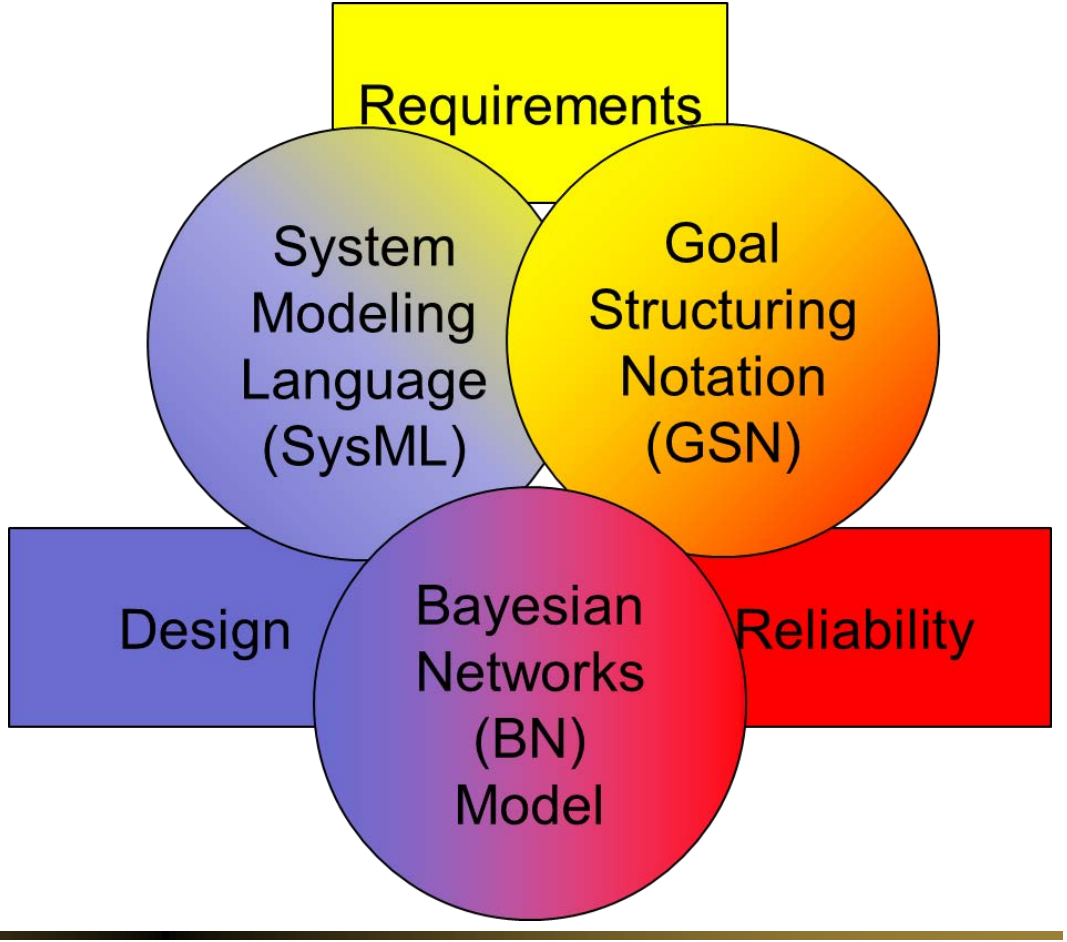
- **Reasons for Activity interaction**
  - Commercial parts (COTS)
  - Document-centric work flow to model-based system engineering
  - Smaller teams
  - System mitigation (for COTS)
  - Shorter schedules for small spacecraft



Demo Vehicle: CubeSats, VU/Amsat AO-85 Results

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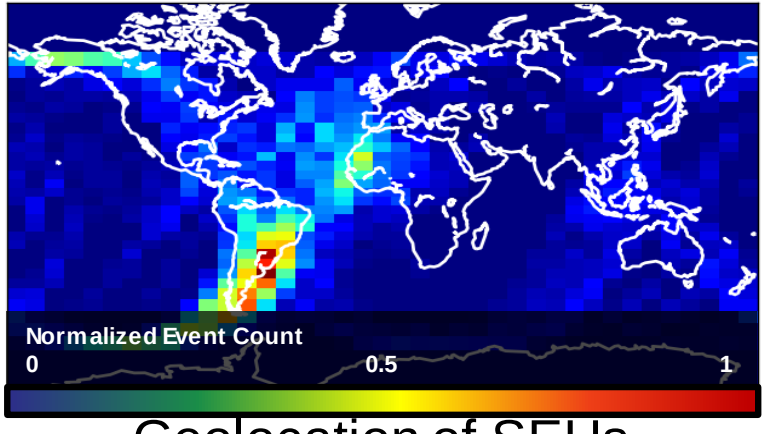
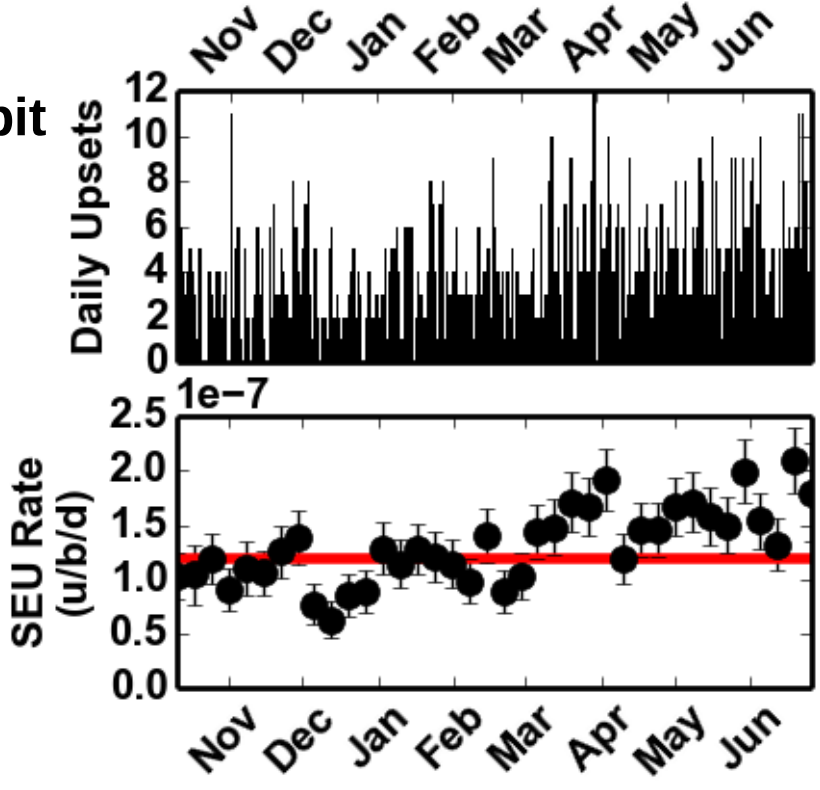
- **Launched October 8th, 2015 as part of ELaNa-XII**
- **800-500 km, 65° inclination orbit**
- **Carries 65nm SRAM SEU experiment**



Geolocation of SEUs



Radiation Reliability Assessment of CubeSat SRAM Experiment Board

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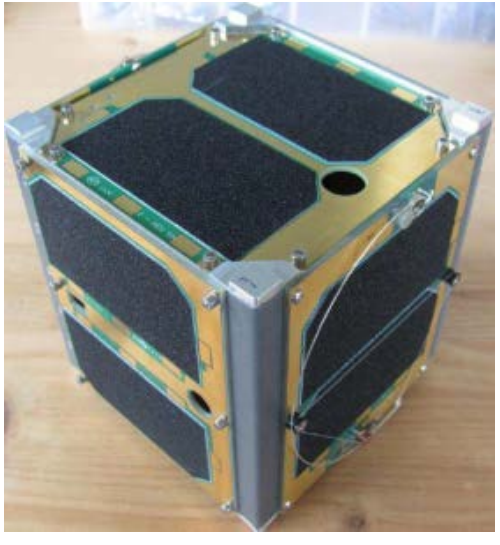
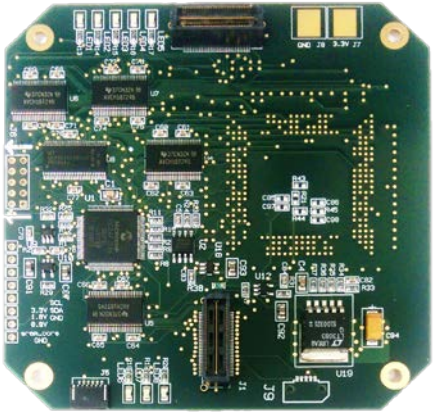
- **Assessment completed on REM**
  - 28nm SRAM SEU experiment
- **Reasons for integrated modeling**
  1. Use commercial off-the-shelf (COTS) parts
  2. System mitigation of SEL
  3. System mitigation of SEFI on microcontroller



Courtesy of AMSAT



System-level RHA:
Block Diagram of 28nm SRAM SEU Experiment

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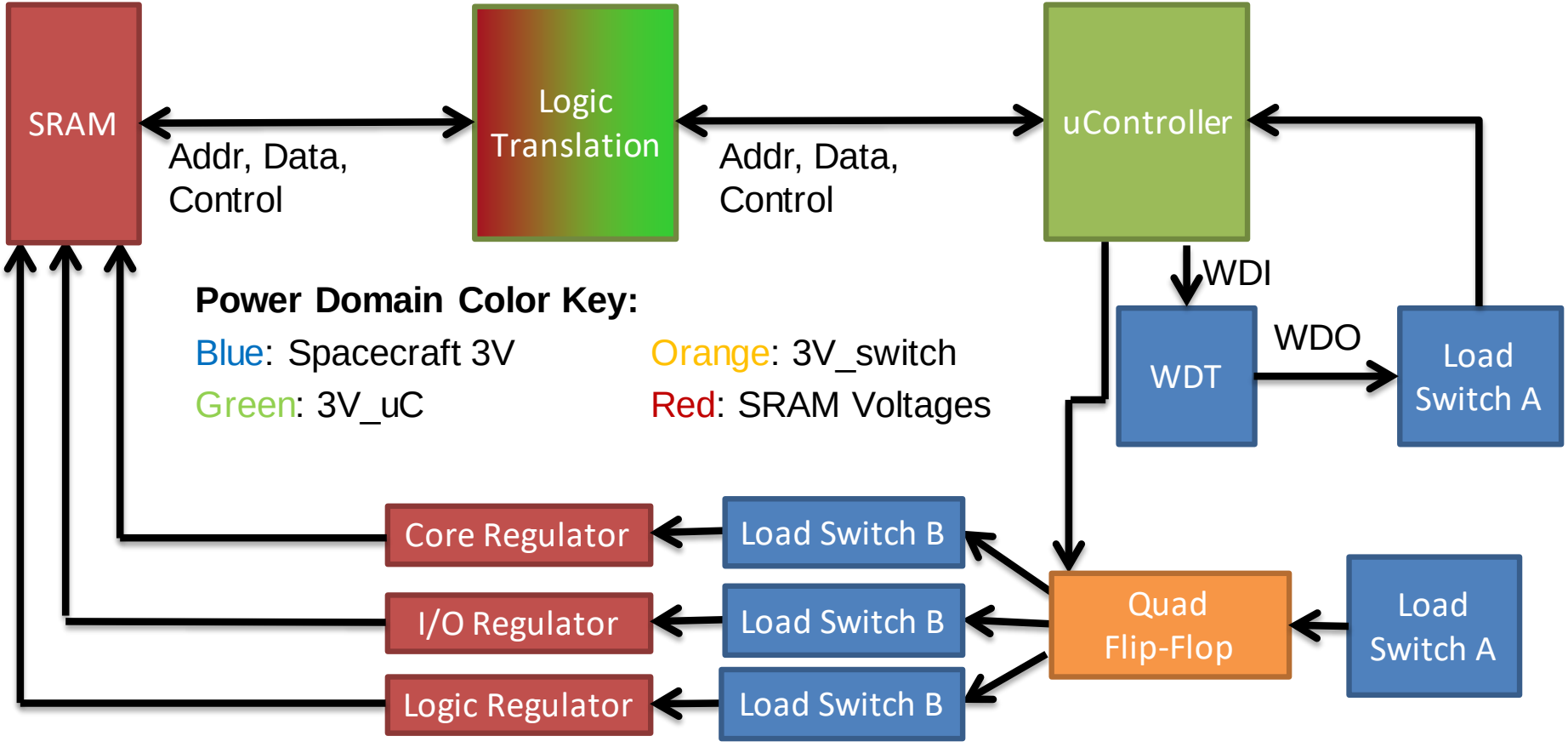

Overview of Model Integration of SysML, GSN, BN

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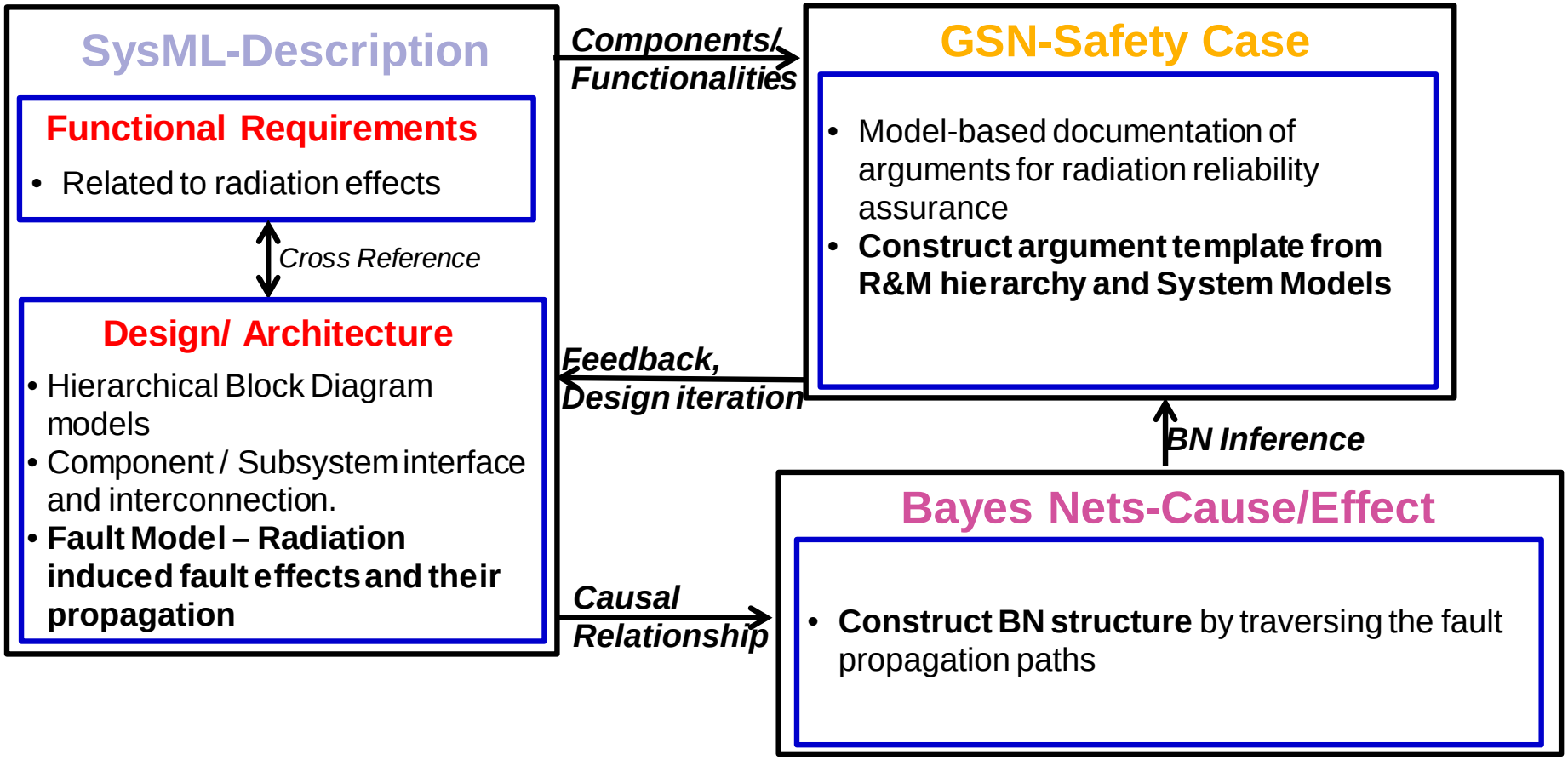

Overview of Modeling Approaches Used

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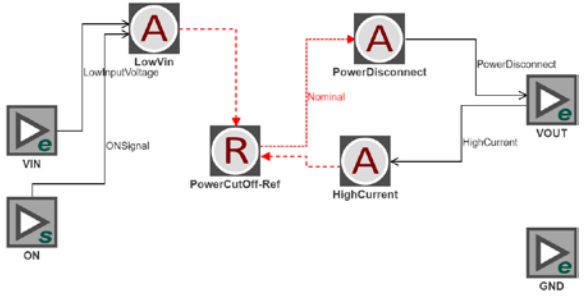
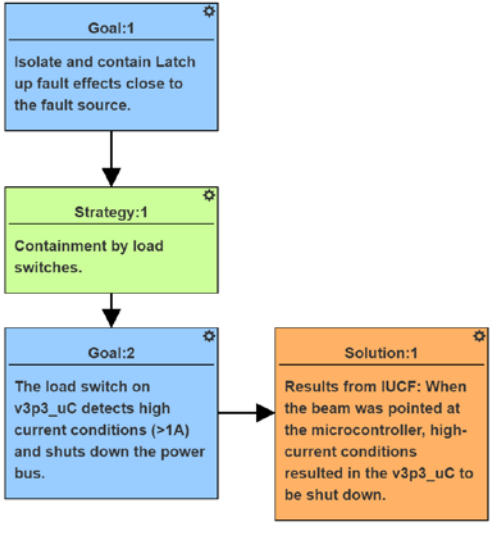
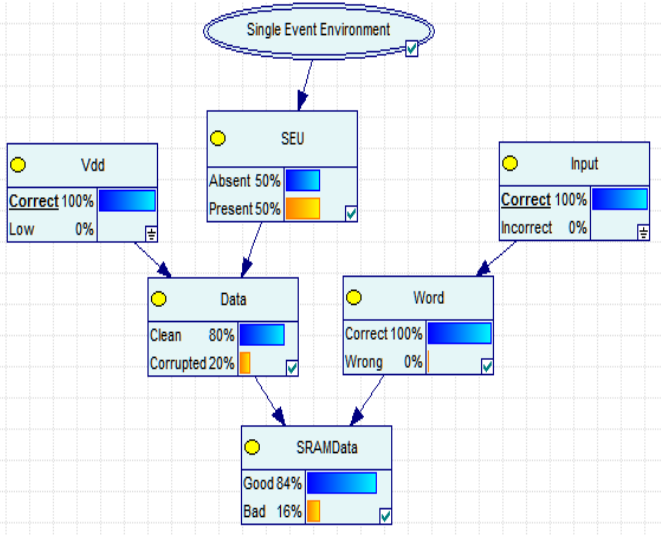
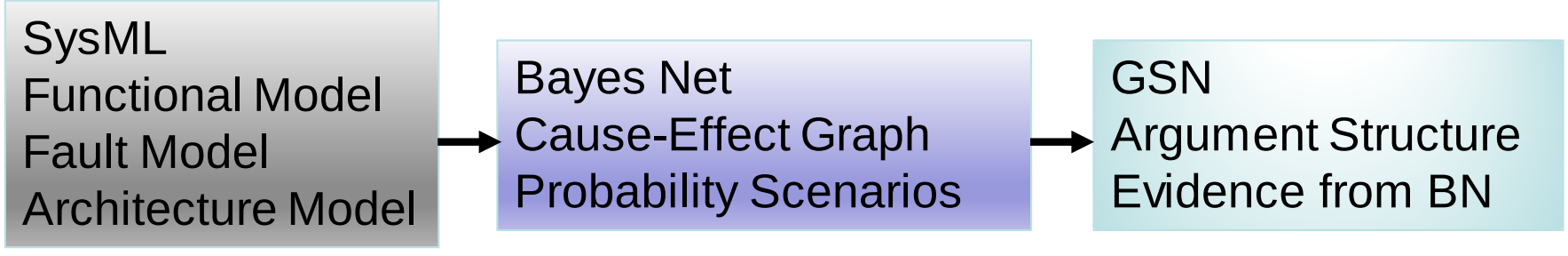
SysML	GSN	BN Network
• Specification of systems through standard notation • Added fault propagation paths	• Visual representation of argument • Goals, Strategies, and Solutions	• Nodes describe probabilities of states • Calculate conditional probabilities from observations
		

Integrated Model-Based Assurance Path



Objectives

-Obtain systematic coverage of possible faults

-Move towards quantitative assessment of risk/reliability

Goal Structuring Notation (GSN): Visual Representation of an Argument

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Strategy: Reasoning step, nature of argument

Goal: Claims of the argument

Context: How the claim or reasoning step should be interpreted. Can be linked to documents or other models.

Justification: Explain why a claim or argument is acceptable

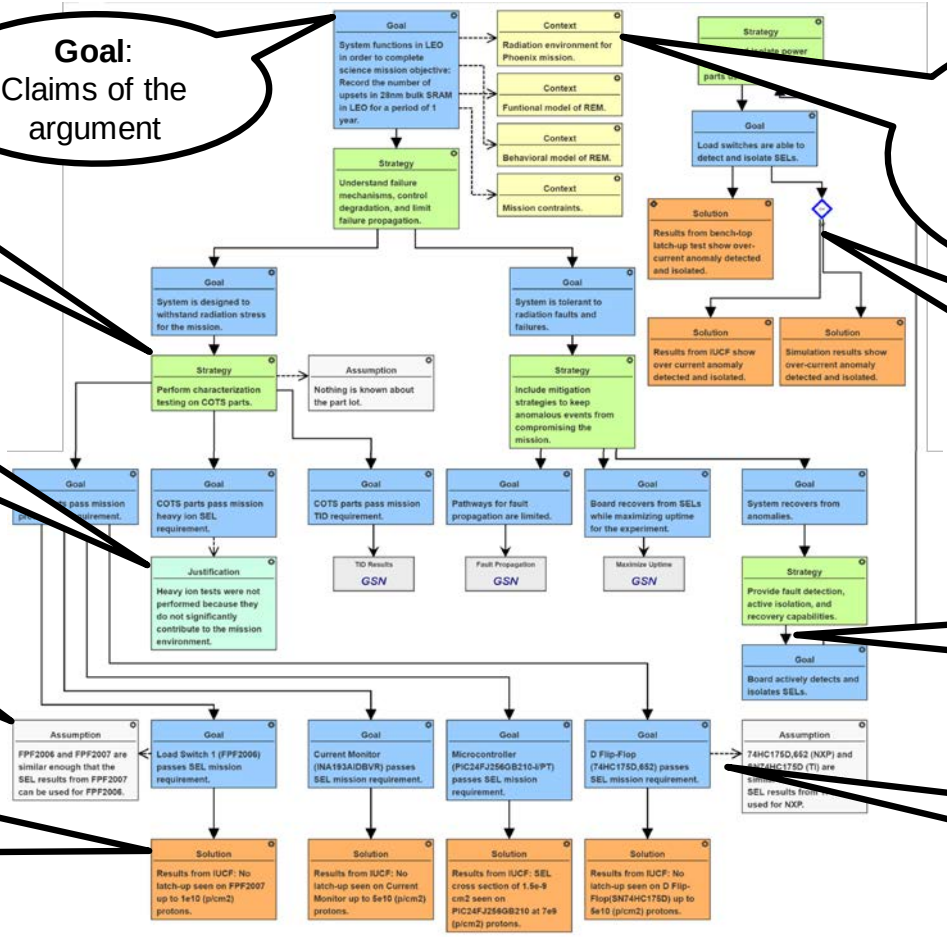
M of N options: M out of N paths can be completed to prove goal

Assumption: Needed for goal or strategy to be valid

Supported by: Inferential or evidential relationships

Solution: Items of evidence. Test reports linked.

In Context of: Contextual relationships



NASA Reliability & Maintainability (R&M) Template

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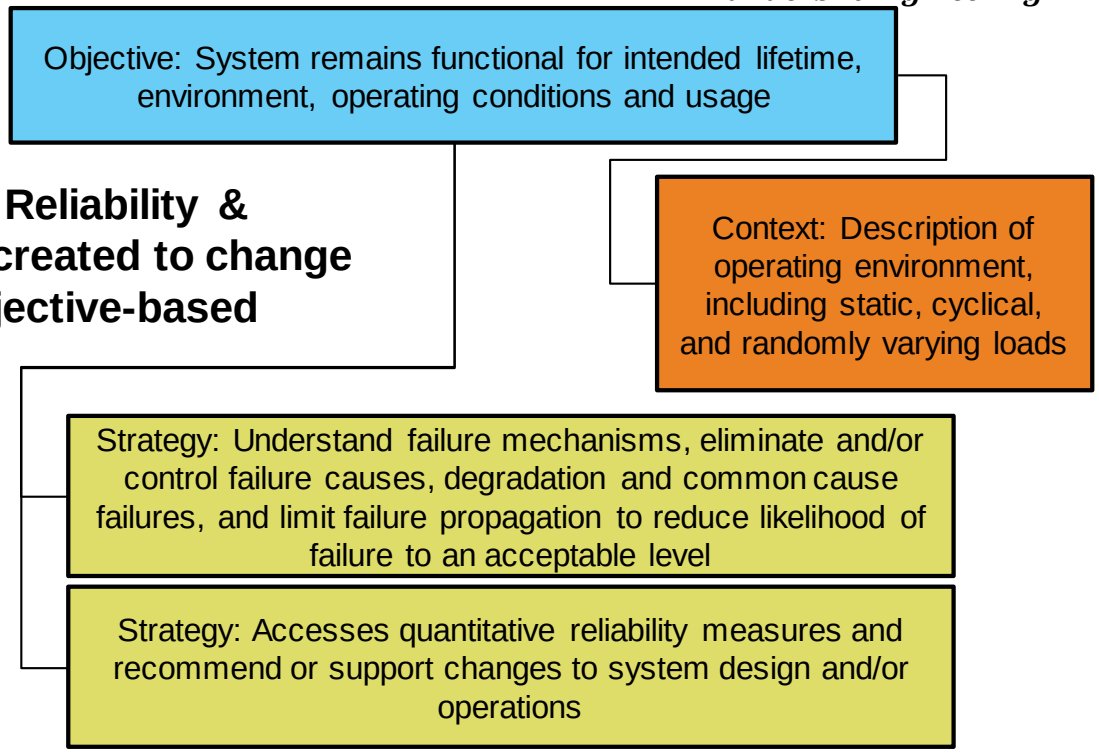
- **Old Paradigm: Reliability proven through list of tests passed**
- **Proposed New Paradigm: NASA Reliability & Maintainability (R&M) Template created to change reliability requirements to be objective-based (Groen, RAMS 2015)**
  - Based on Goal Structuring Notation
  - Created with Class A Missions in mind
  - Graphical structure to reliability requirements allows for integration with MBSE



R&M Template (Groen, RAMS 2015)

- **Can an assurance case for the radiation-reliability of a sub-Class D mission be made? Is it useful?**

Top Level GSN Model of REM Experiment Board

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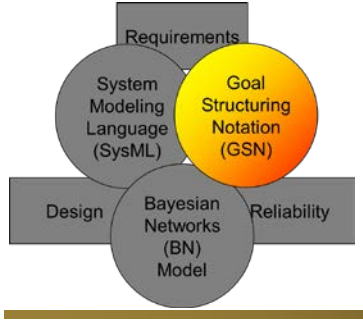
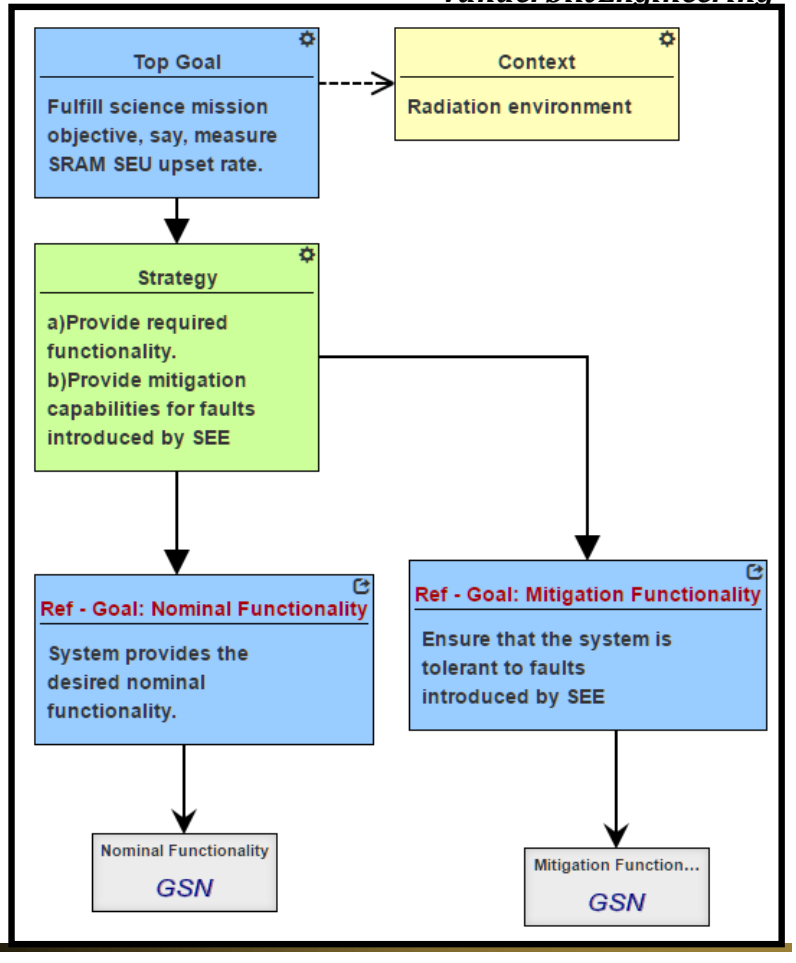
- **Top level goal: Complete science mission objective**
- **Strategies: Provided functionality and mitigate radiation environment**
- **Goals: Validation of "Nominal" and "Mitigation" functionalities**
  - Focused on radiation-induced faults





GSN Models for Single Event SRAM Experiment

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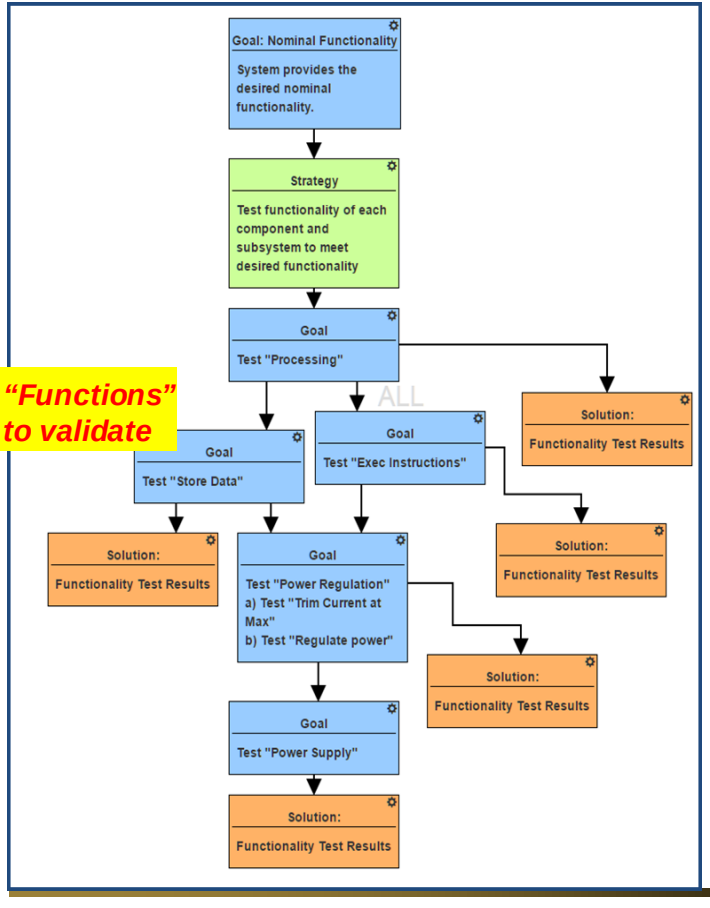
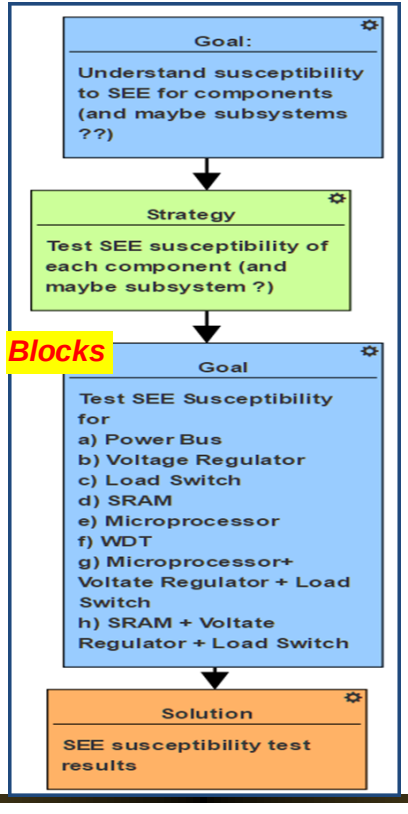
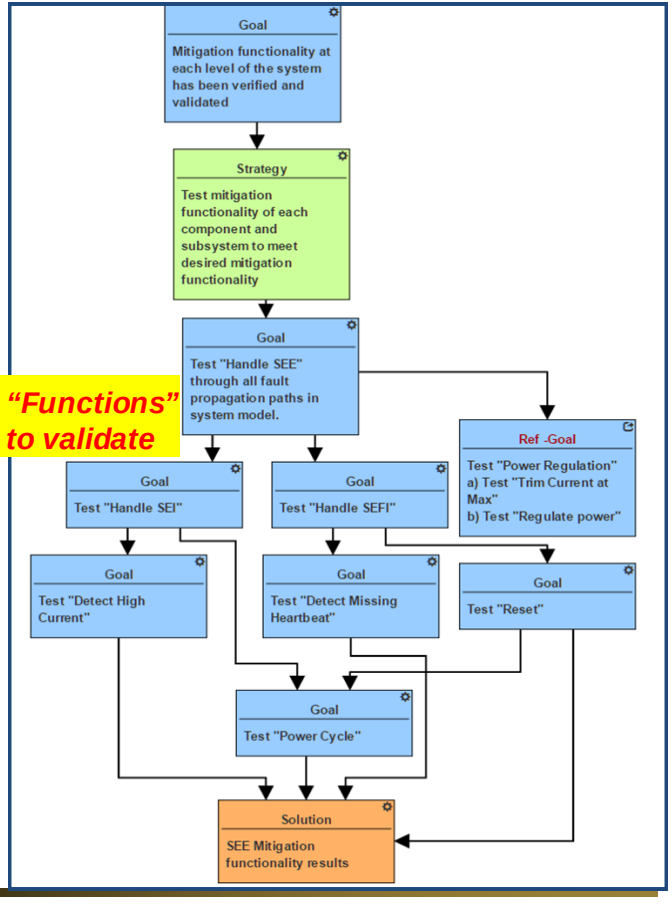
Validate Nominal Functions



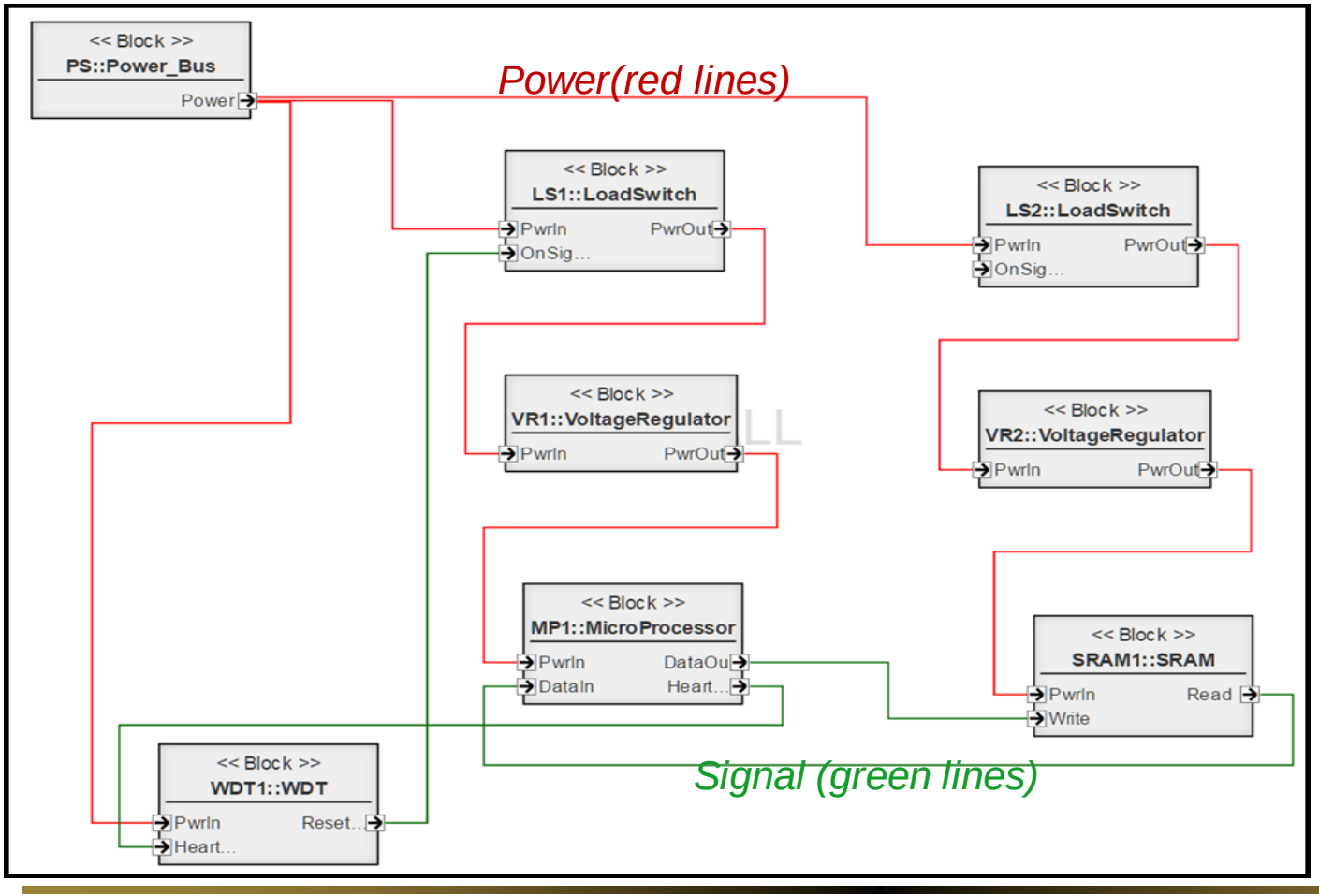
Identify Component Susceptibility

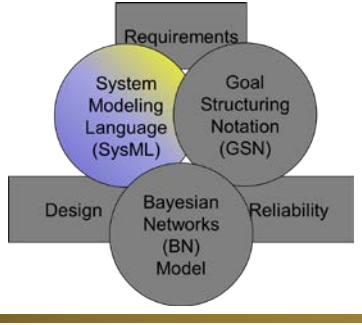


Validate Mitigation Functions



SysML Block Diagram of REM Experiment Board





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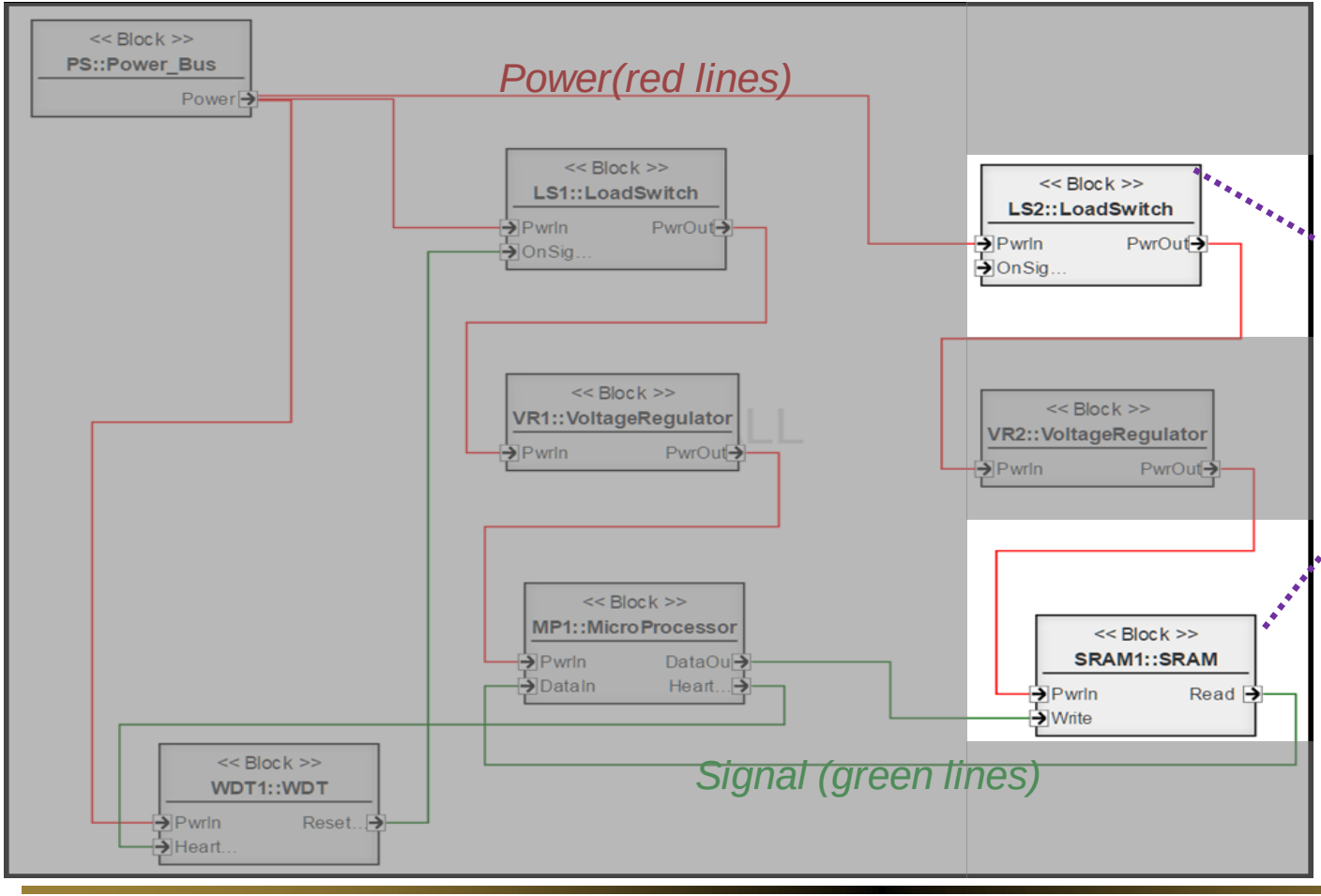
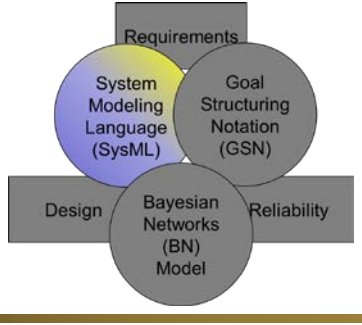
SysML Block Diagram of REM Experiment Board



Focus on Load Switch, SRAM subsystem



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SysML Internal Block Diagram with Fault Propagation Paths

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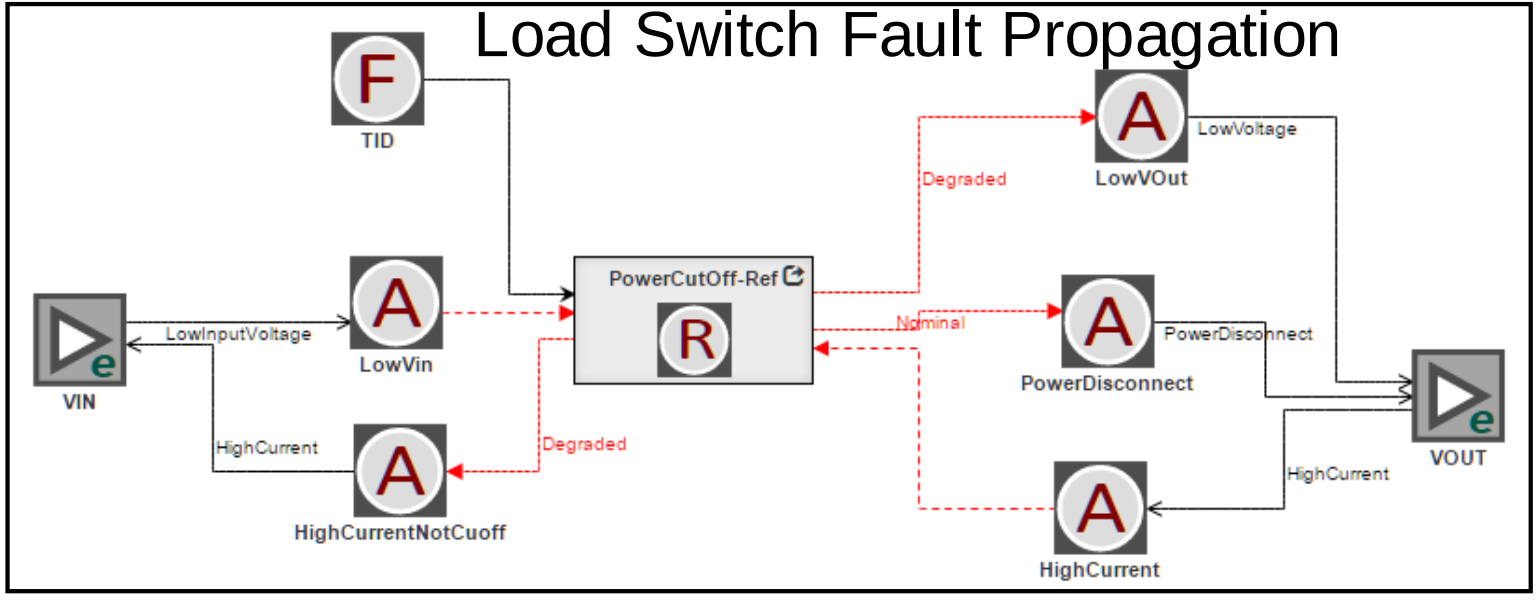
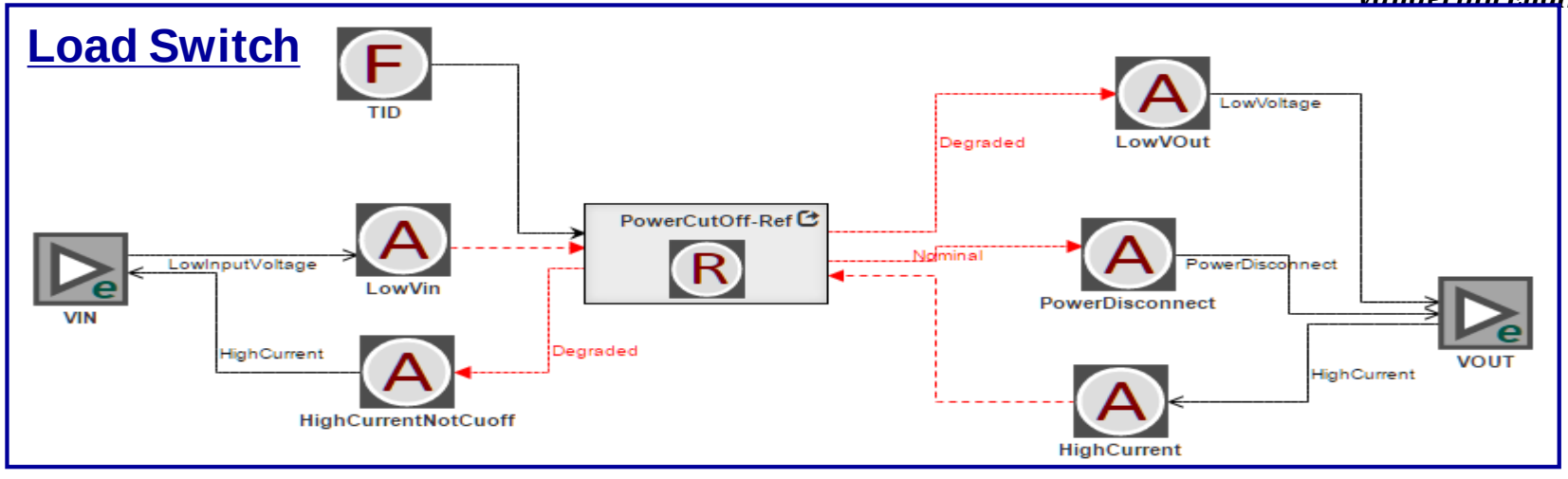
- **Fault (F) Change in physical operation, depart from nominal**
- **Anomaly (A) Observable effect or anomalous behavior from fault**
- **Response (R) Intended response of component to A and F (mitigation)**



Fault Model – Load Switch



- A LowInputVoltage anomaly (from another component) leads to appropriate *Nominal* response from PowerCutOff function, leading to PowerDisconnect
- A HighCurrent anomaly (from another component) leads to appropriate *Nominal* response from PowerCutOff function, leading to PowerDisconnect

- TID fault could affect load switch response, leading to *Degraded* PowerCutOff functionality
  - LowInputVoltage anomaly could be passed on to the component downstream
  - HighCurrent anomaly may not be detected or cutoff

SysML Internal Block Diagram with Fault Propagation Paths

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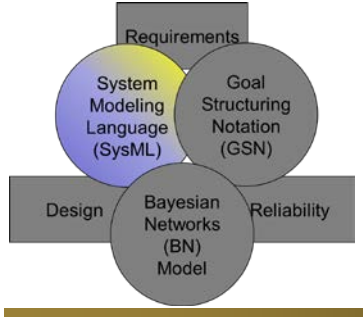
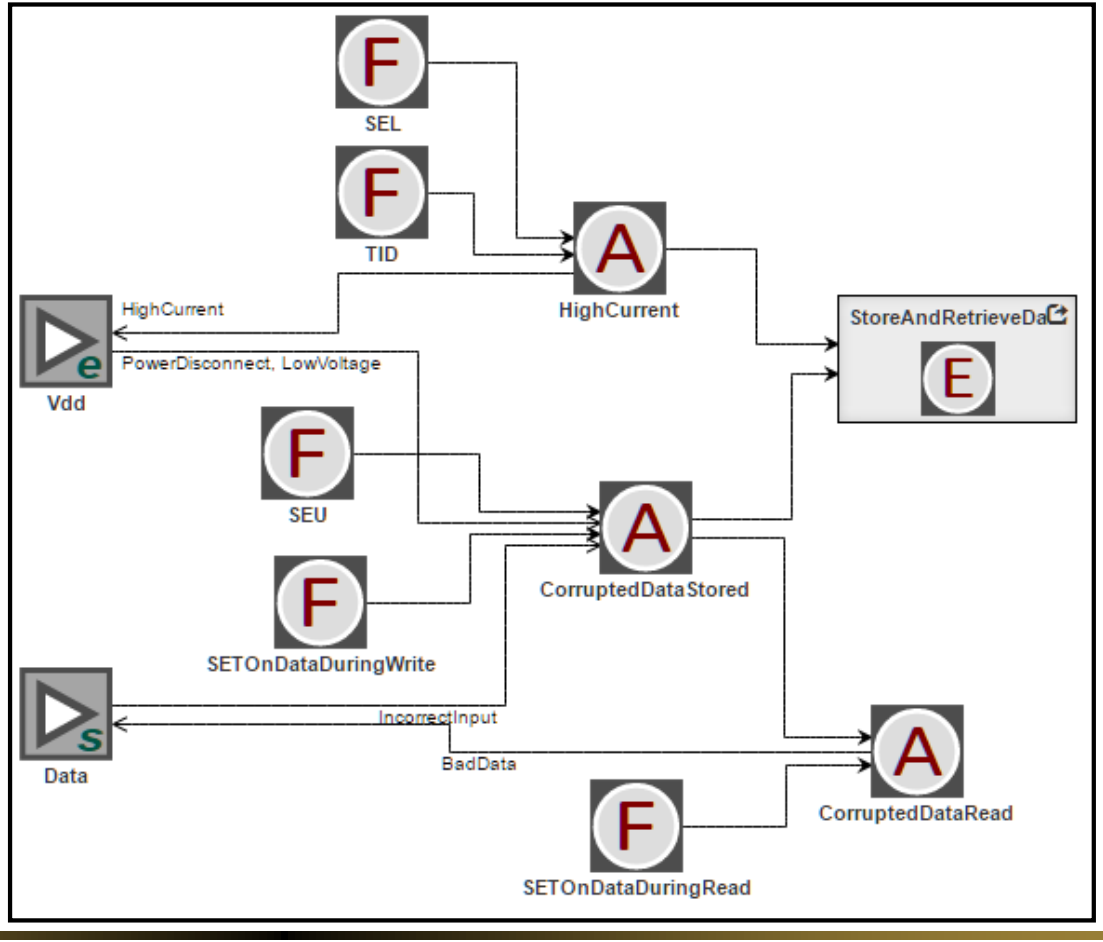
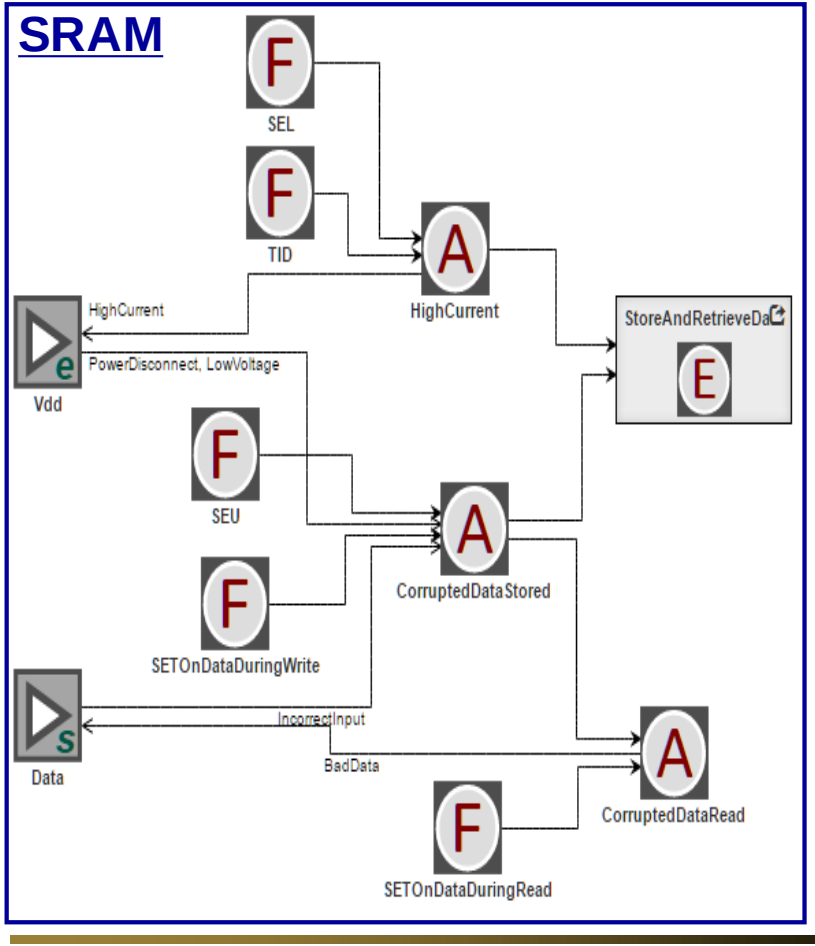
- **SRAM**
  - Effects (E) impact on functionality
  - Faults/Anomalies flow through ports to affect other components



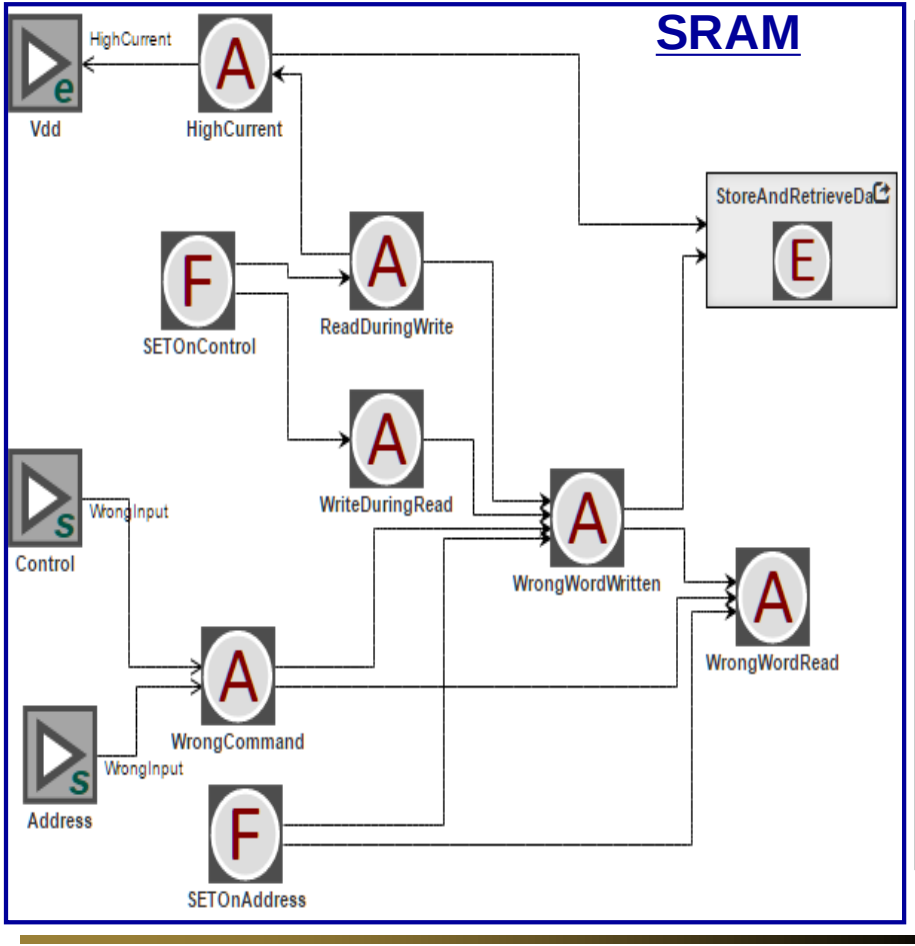


Fault Model - SRAM



- SEL, TID faults could lead to HighCurrent anomaly
- HighCurrent failure-effect is output to other components through the Vdd power-port
- SEU, SETonDataDuringWrite faults could lead to CorruptedDataStored anomaly
- PowerDisconnect, LowVoltage, IncorrectInput failure-effects from other components could also lead to CorruptedDataStored anomaly
- CorruptedDataRead anomaly results from CorruptedDataStored anomaly as well as SETonDataDuringRead fault. Further, it leads to output of BadData failure-effect
- StoreAndRetrieveData functionality can be degraded (Effect node) due to HighCurrent as well as CorruptedDataStored anomalies

Fault Model – SRAM cntd.



- SETOnControl fault could lead to ReadDuringWrite and WriteDuringRead anomalies, which could lead to WrongWordWritten anomaly.
- ReadDuringWrite could lead to HighCurrent anomaly.
- WrongInput failure-effect from other components to Control or Address ports could lead to WrongWordWritten or WrongWordRead anomalies.
- SETonAddress fault could lead to WrongWordWritten or WrongWordRead anomalies.
- StoreAndRetrieveData functionality can be degraded (Effect node) due to HighCurrent as well as WrongWordWritten anomalies.

Custom Modeling Environment - WebGME

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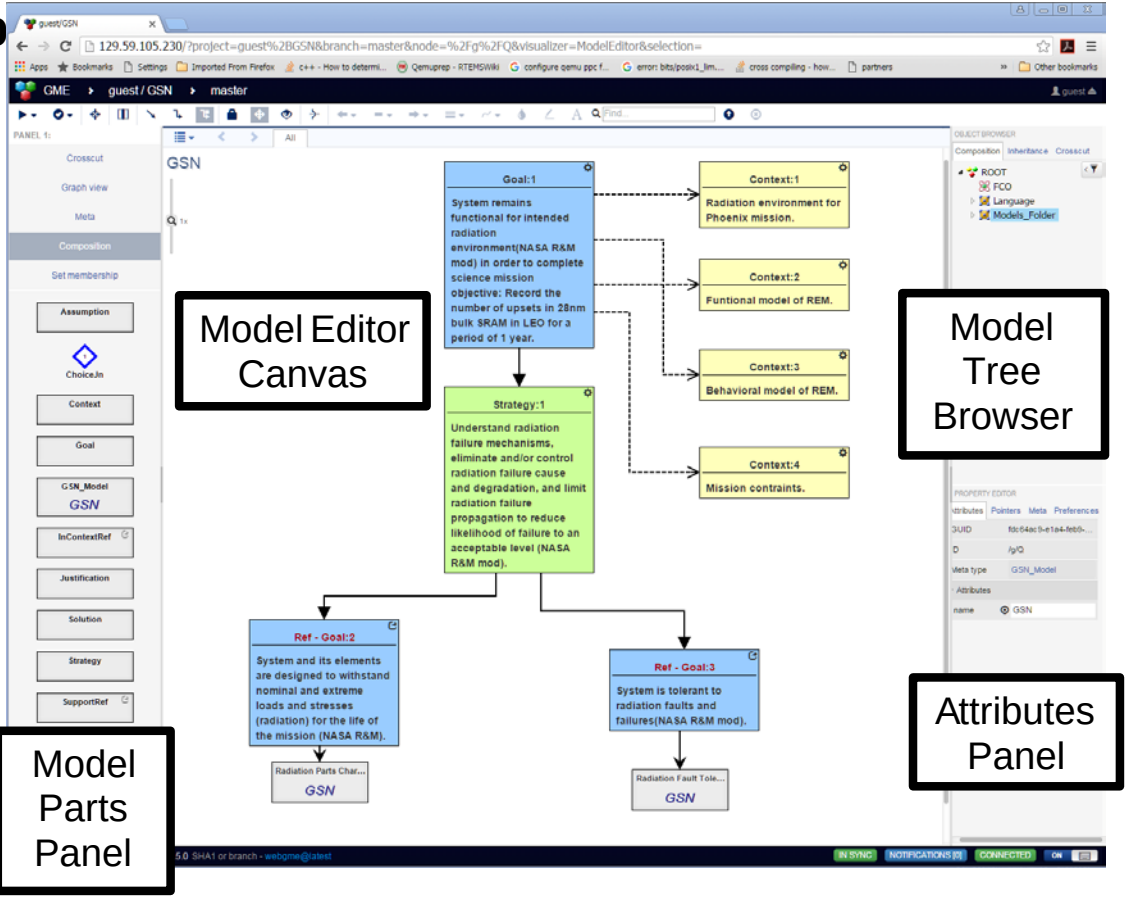
- **WebGME is used to develop the modeling framework**
- **Models include:**
  - Goal Structuring Notation (GSN)
  - System model (SysML)
  - Fault Propagation
  - Function/Behavior Models
- **Allows for links across models**
- **Links to external documents**

https://webgme.org/



Model-Based Assurance Case (MBAC+ (=WebGME)) for Radiation Hardness Assurance Activities

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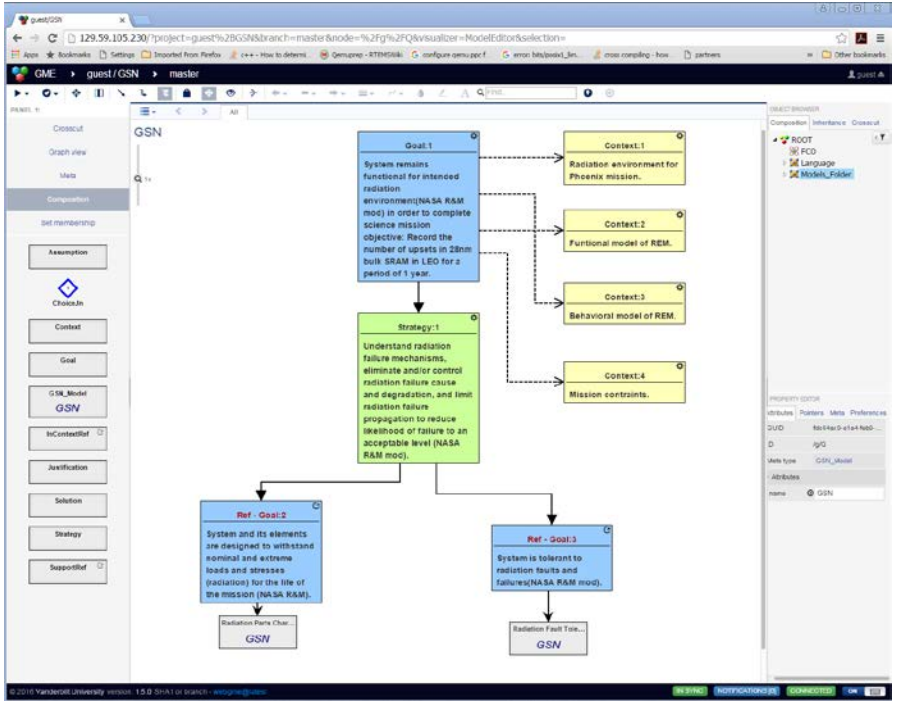
- Tutorial at **NSREC 2017 Tuesday, July 18th**, during lunch
- Learn how to use NASA's Reliability and Maintainability Template to construct a radiation reliability assurance case
- Modeling environment also supports SysML Block Diagram modeling with fault propagation (no Bayesian nets yet)
- Browser based
- Free non-proprietary site hosted on Amazon (AWS) (like Crème)
- Free images of site for proprietary or export controlled modelling for hosting on Amazon GovCloud or internal servers



Bayesian Network Models

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BN Structure

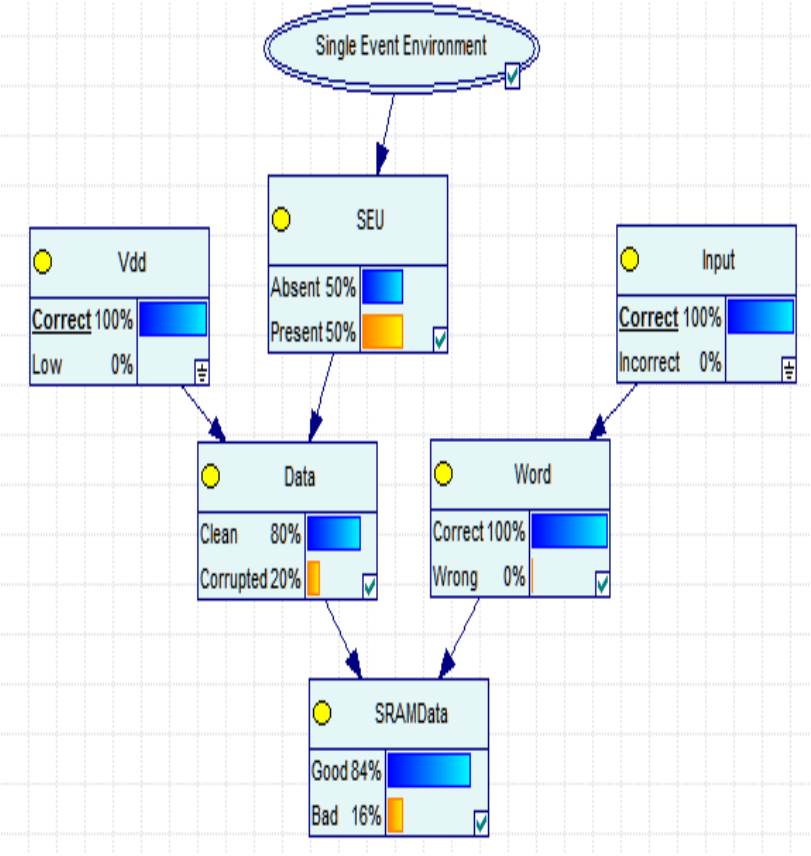
- Node are probabistic or determinstic variables in a domain
- Nodes can also be discrete or continuous.
- Directed edges capture the dependency relationship between the nodes

BN Parameters

- State of a probabilistic nodes are expressed as probability (or probabistic distribution)
- Dependency relationship of a child node on its parents is expressed in terms of conditional probability tables (or likelihood functions)

BN Inference

- The BN inference process estimates the probabilistic distribution (posterior) of each node, when the states of certain nodes are fixed (observation/ evidence)



Development of Bayesian Network Models from SysML

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SysML models
- Architecture, Fault Models
- Functional requirement models

Traverse design model from each fault to generate flat causal relationship graph.

For each component/ subsystem sub-graph, add functionality (leaf node) based on functional model (if not present).

Merge common nodes across fault paths - faults, anomalies, functional effects and responses.

Add additional edges based on functional dependency. Add additional nodes (edges) for higher level functions (functional model).

Prune graph based on expert knowledge, convenience etc.

Identify states, likelihood relations, prior and conditional probabilities.

SysML Fault Models SRAM/Load Switch Sub-System

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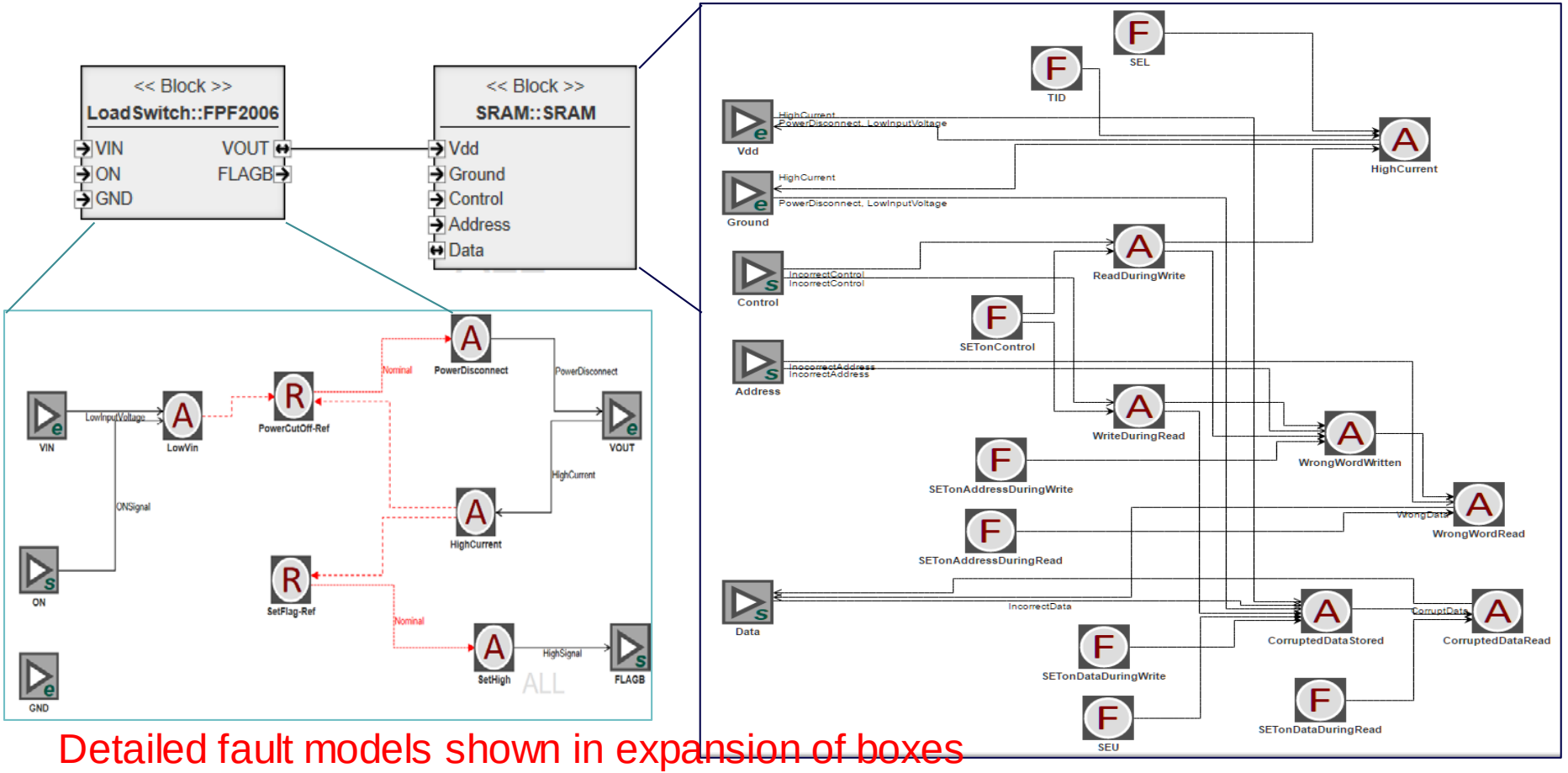

Detailed fault models shown in expansion of boxes

Bayesian Network SRAM/Load Switch (1/3)

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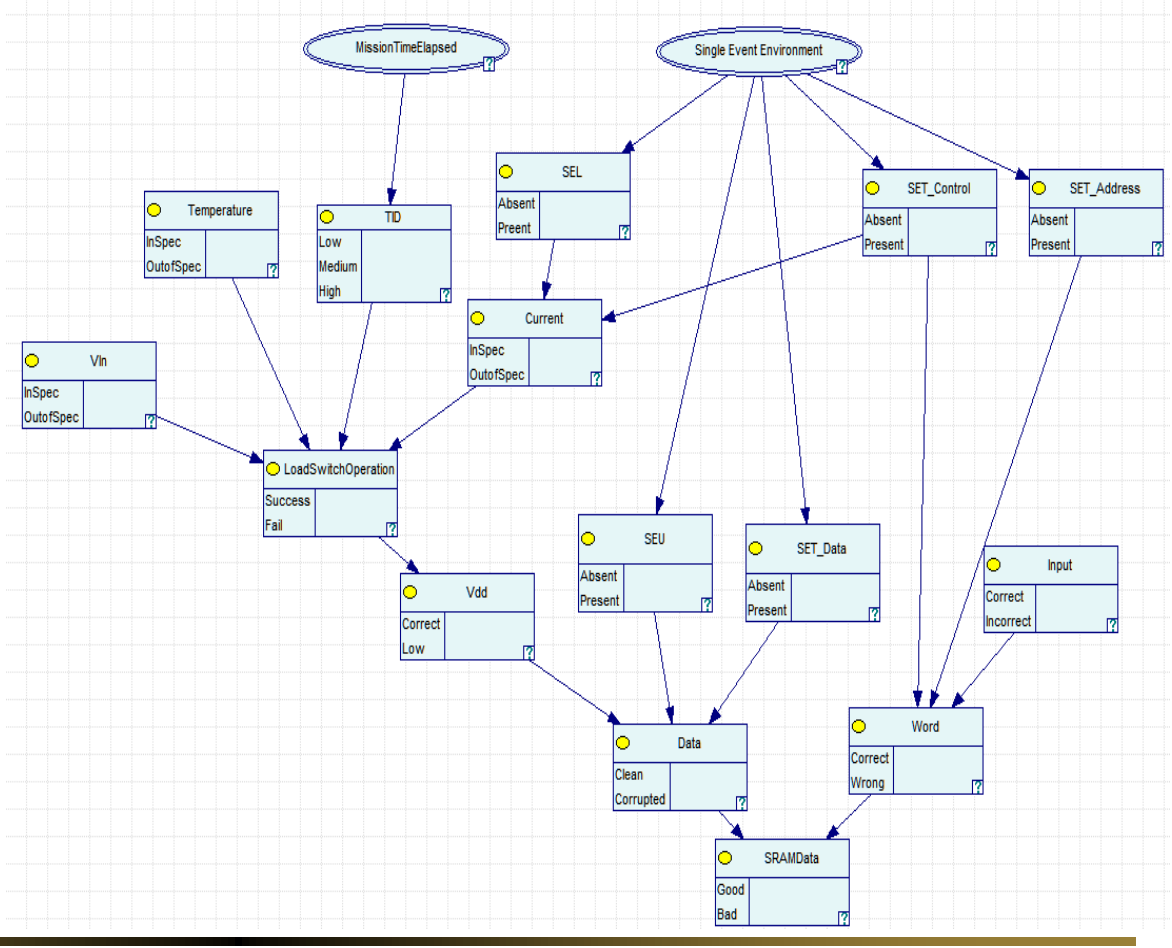
Determinstic Node Description:

- MissionTimeElapsed: Time elapsed in the mission can be set to any of the following states
  - < 1 year for Low TID
  - 1-2 year for moderate TID
  - > 2 year for High TID

- SingleEventEnvironment: The current environment can be set to any of the following states
  - Low Rate Region: Low probability of SEE occurrence.
  - South Atlantic Anomaly (SAA): Greater probability of SEE occurence

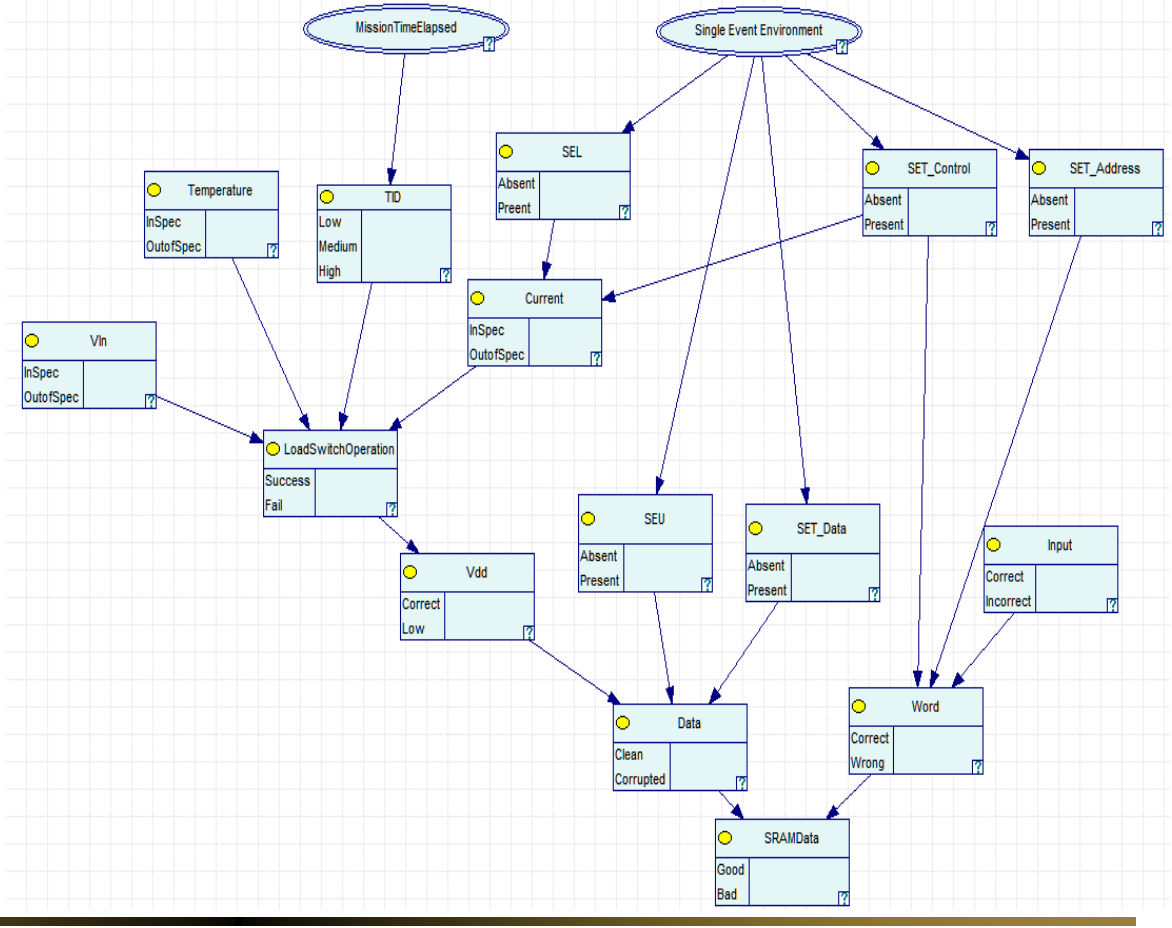


Bayesian Network SRAM/Load Switch (2/3)

Probabilistic Nodes Description (1/2):

Probability of …

- TID : Presence/level of TID
- SEL: Occurrence of Latch up
- Current: Supply current being in spec
- Temperature: Load Switch temperature being in spec.
- Vin: Load Switch input voltage being in spec
- LoadSwitchOperation: Quality (“success”) of load switch operation to cut off power



Bayesian Network SRAM/Load Switch (3/3)

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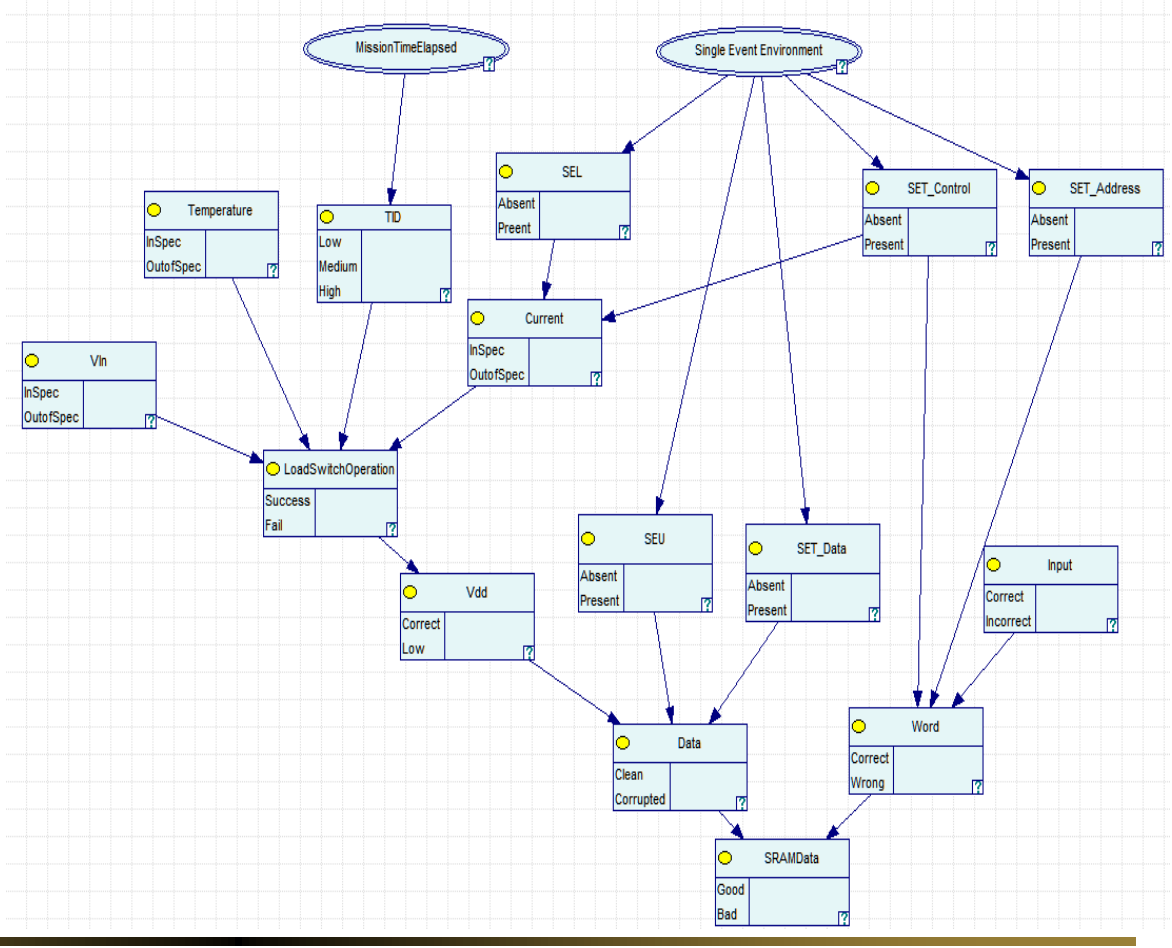
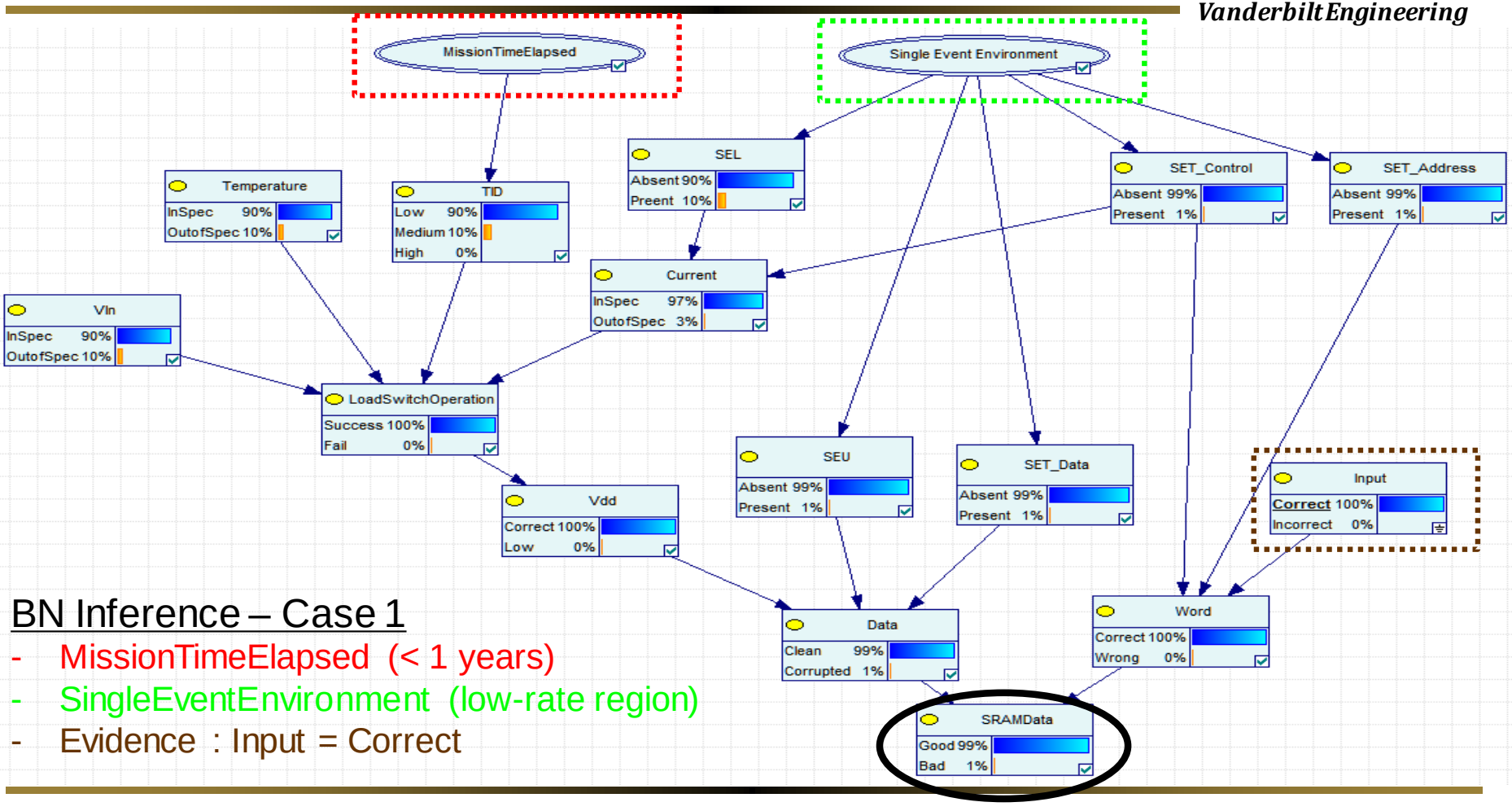
Probabilistic Nodes Description (2/2):

Probability of …

- SEL: Occurrence of Latch up
- SEU: SRAM- occurrence of upsets
- SET_x (x=control, address, data): SRAM - occurrence of transients on control, address, data ports
- Input: Incorrect input to SRAM
- Vdd: Input Power to SRAM being correct or low
- Data: SRAM data being correct or corrupted
- Word: SRAM words being correct or wrong
- SRAMData: SRAM Data being correct



Bayesian Network Inference – Case 1



BN Inference – Case 1

- MissionTimeElapsed (< 1 years)
- SingleEventEnvironment (low-rate region)
- Evidence : Input = Correct

Bayesian Network Inference – Case 2

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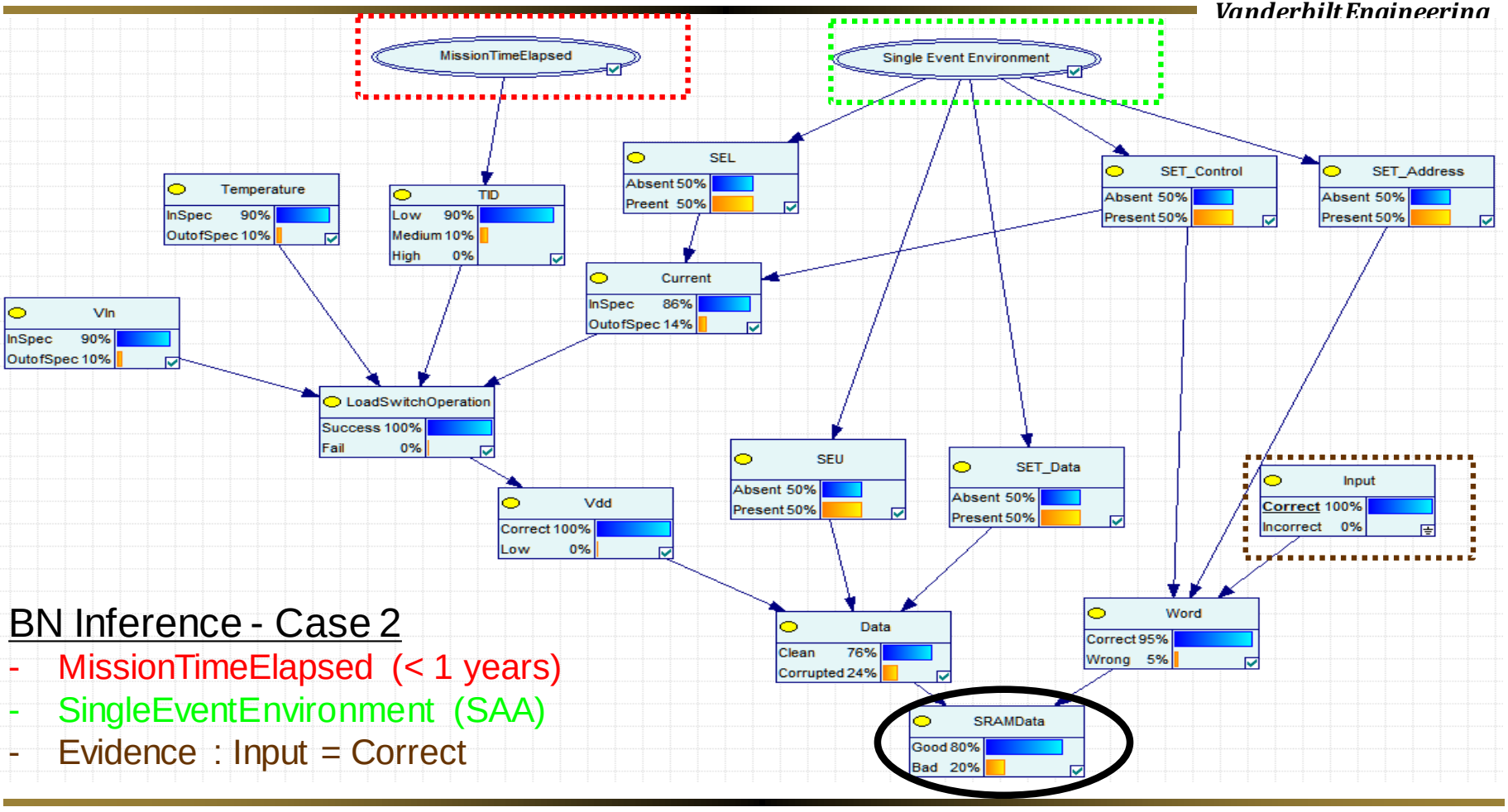
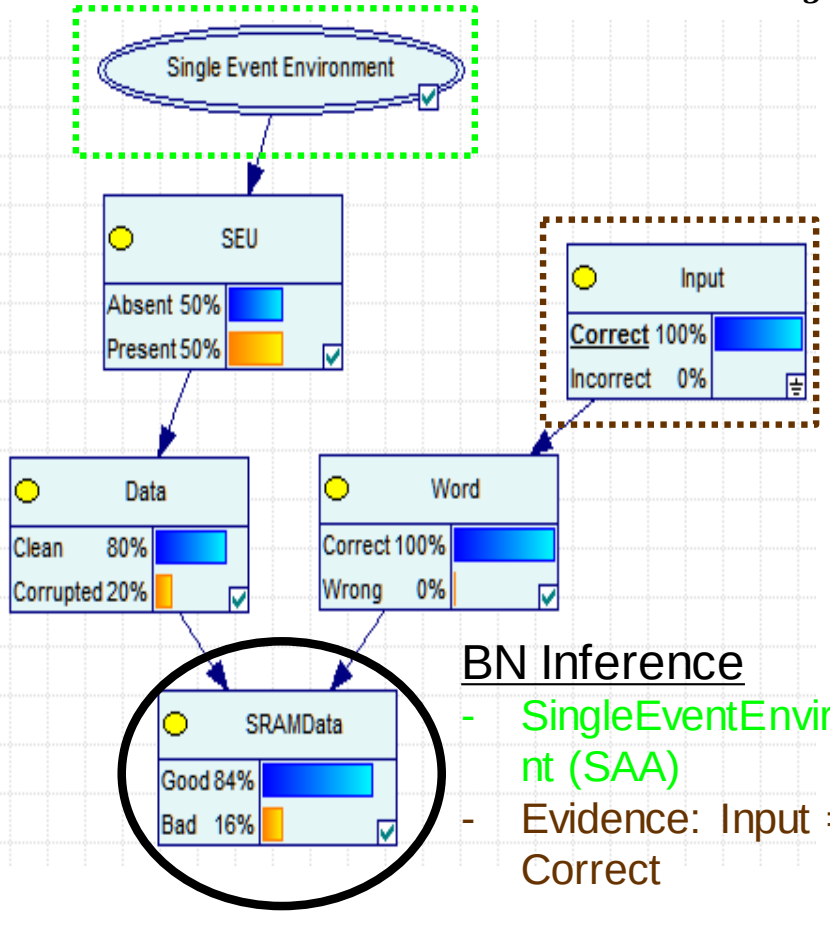


BN Inference - Case 2

- MissionTimeElapsed (< 1 years)
- SingleEventEnvironment (SAA)
- Evidence : Input = Correct

Inference with Pruned Bayesian Network

- BN Pruned based on
  - Load Switch operates correctly for mission time of 2 years
  - Remove Load switch portions
  - 2. SET probability of affecting SRAM is very little
  - Remove SET_* nodes
  - 3. Input to SRAM is correct
  - Input (data)= Correct
- SEE environment set to LEO or SAA
- Shows sensitivity of SRAM data to SEE environment



BN Inference

- SingleEventEnvironment (SAA)
- Evidence: Input = Correct

Transition and Related Work with JPL

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Related Project with JPL

- Command and Data Handling (C&DH) Board
- Build reliability models and Safety case for subset of C&DH functions

Lunar Flashlight 6U Form Factor

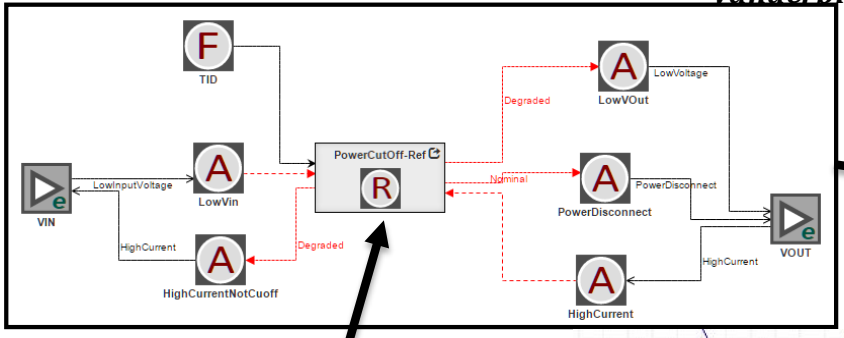
Sphinx C&DH Board

"CubeSat flight system development for enabling deep space science," T. Imken et al, IEEE Aerospace Conference 2017

Summary

Vanderbilt Engineering

- **Developed integrated process for model-based assurance case for radiation reliability**
- **Constructed example SysML models augmented with radiation-induced faults and propagation**
- **BN inference "observations" used to assess impact of various faults on SRAM performance**



Gives structure to