Reliability Assurance of CubeSat Payloads using GSN, Bayesian Nets and Radiation-Induced Fault Propagation Models

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Small Satellite TIM 10/11/17

Integrated System Design for Radiation Environments*

Requirements

*This slide and many of the following from: R. Austin, "Reliability Assurance of CubeSat Payloads using Bayesian Nets and Radiation-Induced Fault Propagation Models," Single Event Symposium 2017

Design

Reliability

Integrated System Design for Radiation Environments

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SEAM paradigm: System Engineering and Modeling

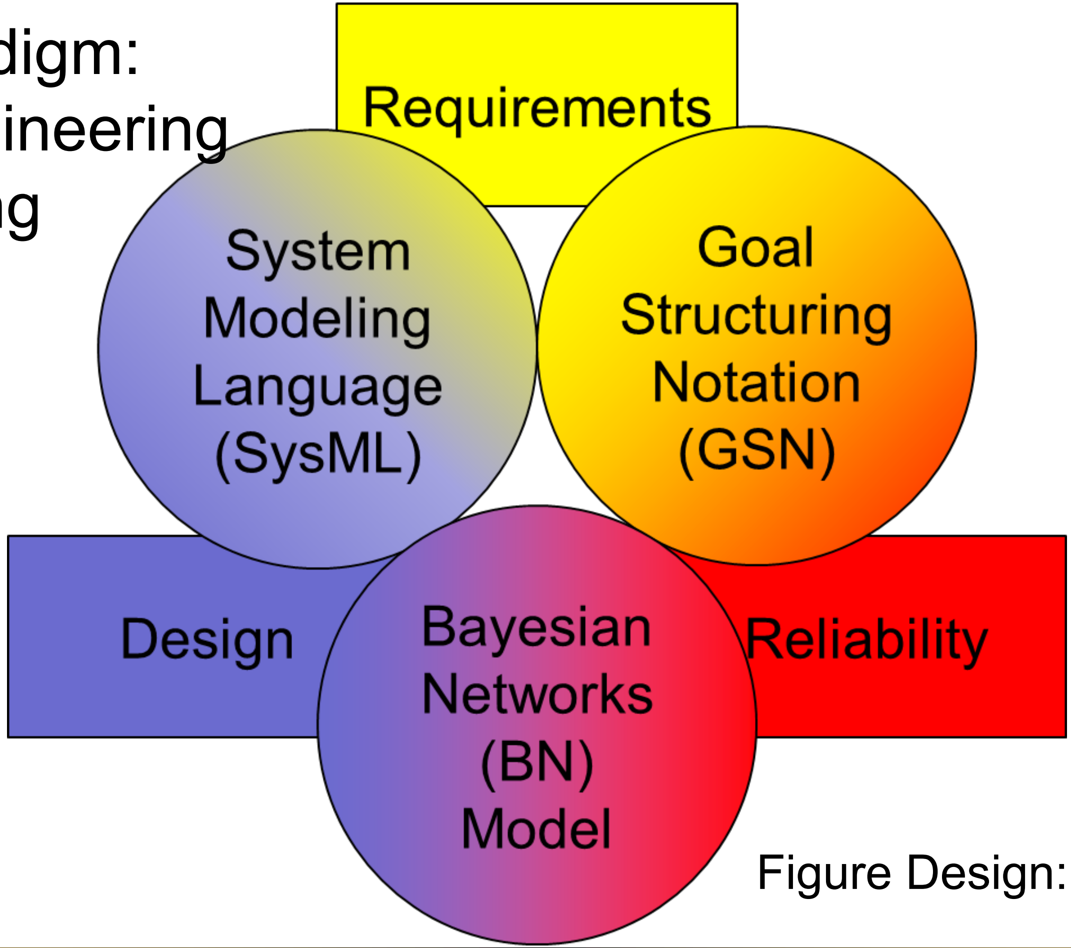

Figure Design: Rebekah Austin

Motivation for Alternate Reliability Approach

- Shift from document-centric to model-centric repository of design information (SysML)
- Shift from prescriptive reliability paradigm to objectives-based paradigm for reliability
  - NASA-STD-8729.1A Reliability and Maintainability Std.
  - Goal Structuring Notation (GSN)
- Increased use of COTS parts on spacecraft
  - Relatively little info on physics of parts available from manufacturers
  - High variability in radiation response of COTS parts
  - Well-suited to probabilistic modeling (Bayesian nets)
- Rapid acceptance and deployment of small spacecraft
  - Short schedule, limited budget and resources
  - Extensive radiation testing and rad-hard parts not feasible

Chronological Overview of Research Effort

- Year 1 (FY 2016): Use of GSN to create a safety case for the impact of single events on a Cube Sat experiment board
  - Sponsored by John Evans (OSMA/HQ) and Ken LaBel (NEPP)
- Year 2 (FY 2017): Development of SysML/GSN/BN model on Cube Sat Experiment board
  - Sponsored by John Evans (OSMA/HQ) and Ken LaBel (NEPP)
  - Development and launch of public website deployed on AWS
- Year 2 (FY2017): TID and Reliability Modeling of Sphinx C&DH board
  - Sponsored by Harald Schone and Phillipe Adell (OSMS) at JPL
  - First task: deterministic modeling of TID impact on system parameters
  - Second task: application of SEAM modeling to Sphinx board

Chronological Overview –Proposed Work

- Year 3 (FY 2018): Reliability of Cube Sat Board
  - Improve SysML import compatibility (e.g. MagicDraw),
  - move into automatic creation of Bayesian nets
  - Integrate with other reliability approaches
  - Sponsored by Ken LaBel (NEPP) and John Evans (OSMA/HQ)
- Year 3 (FY2018): TID and Reliability Modeling of Sphinx C&DH board
  - TID modeling task: Work towards higher fidelity modeling, incorporation of software in simulation
  - SEAM tasks: create model library for Sphinx board components, interface SEAM modeling to IRIS system modeling (UCLA)
  - Sponsored by Harald Schone and Phillipe Adell (OSMS) at JPL

Foundation: NASA Reliability & Maintainability (R&M) Hierarchy

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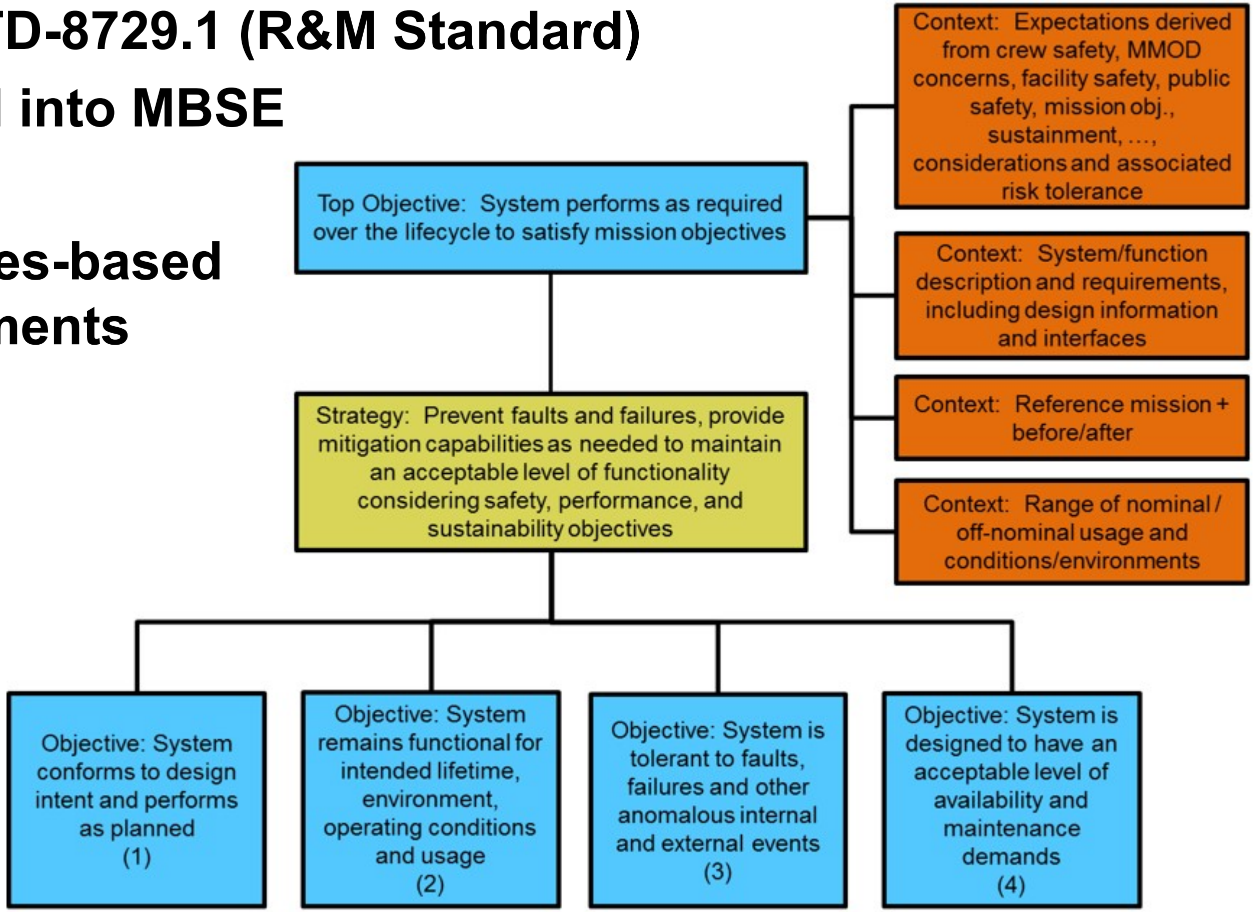
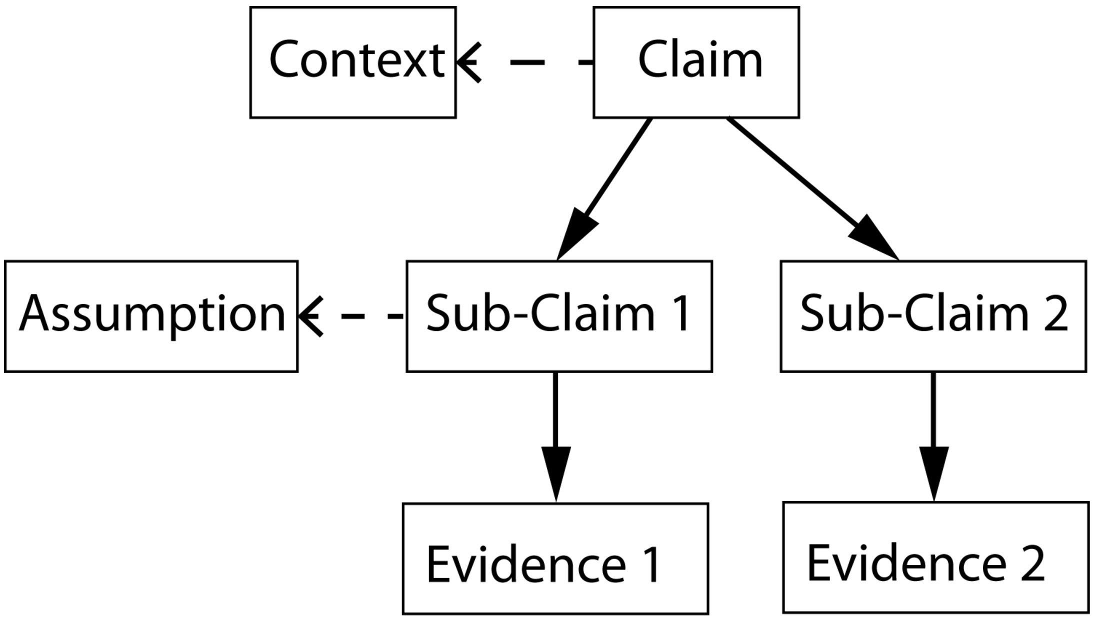
- Basis of NASA-STD-8729.1 (R&M Standard)
- Incorporates R&M into MBSE
- Moves to objectives-based reliability requirements



Graphical Assurance Cases



Argument: "A connected series of claims intended to support an overall claim." [1]

Assurance Case: "A reasoned and compelling argument, supported by a body of evidence, that a system, service or organization will operate as intended for a defined application in a defined environment." [1]

[1] GSN Community Standard Version 1 2011

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

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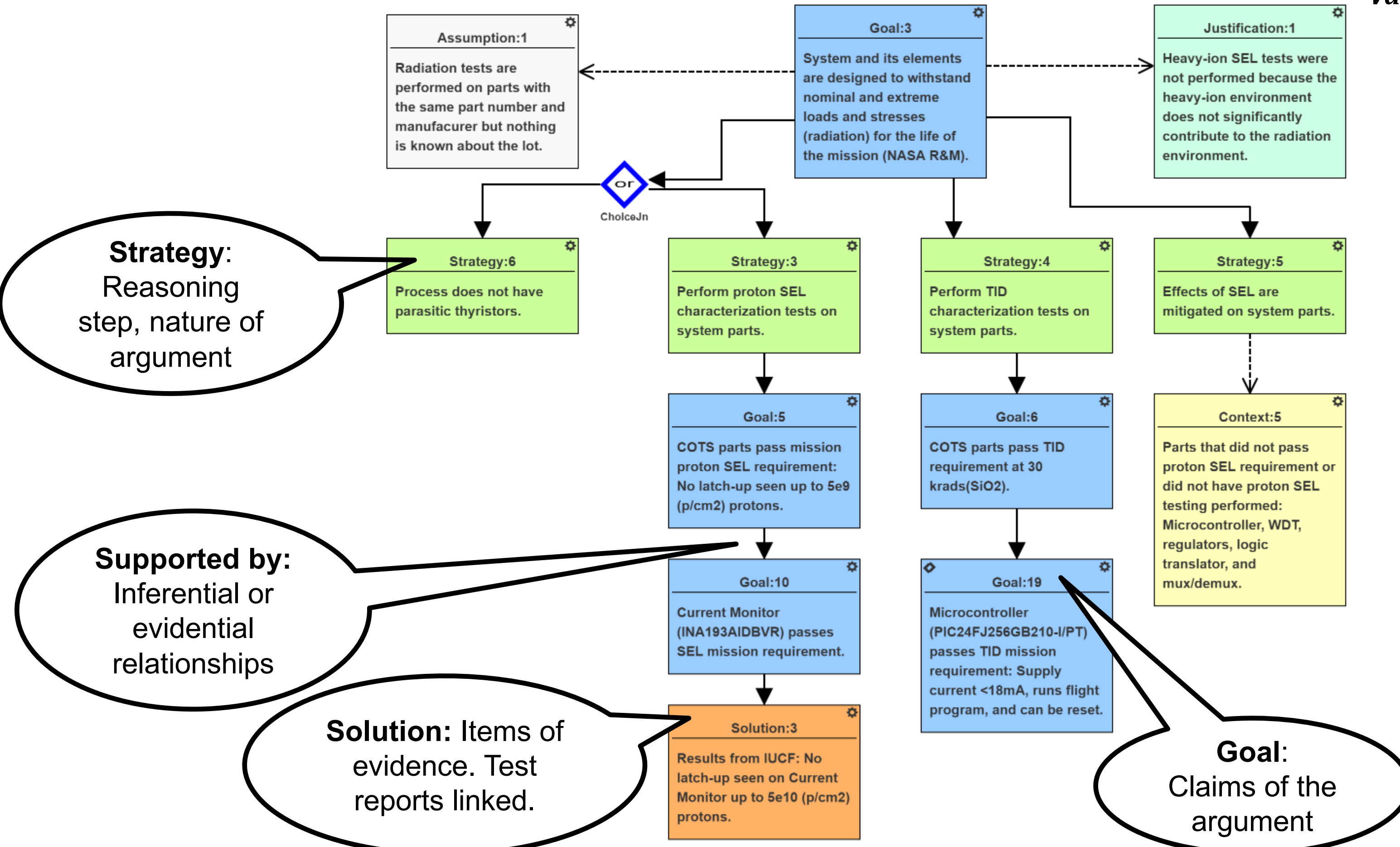

Model Integration of SysML, GSN, and BN*

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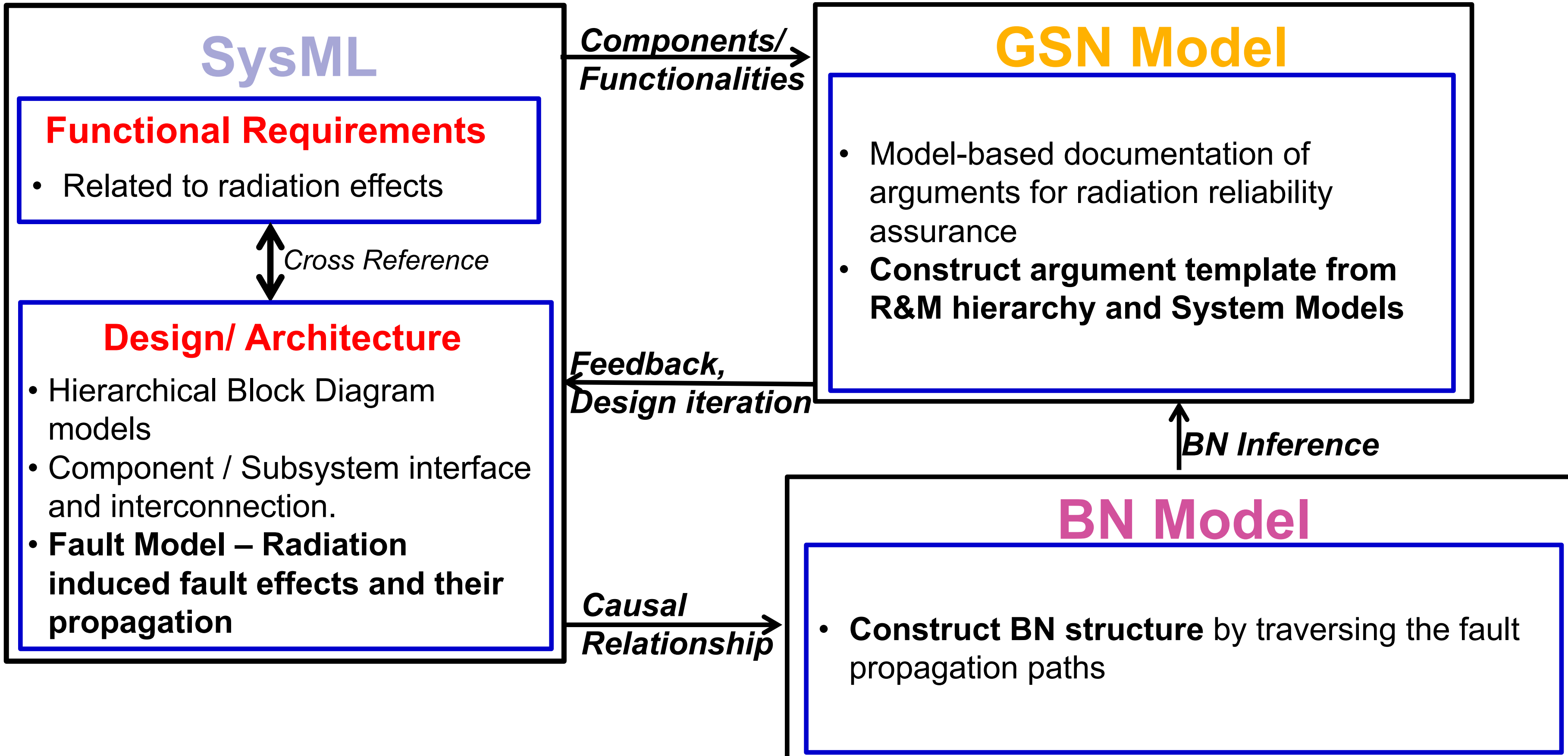

Overview of Modeling Languages Used

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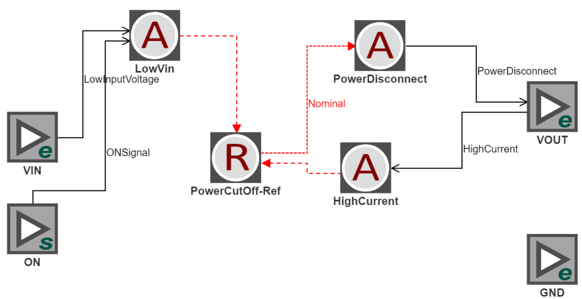
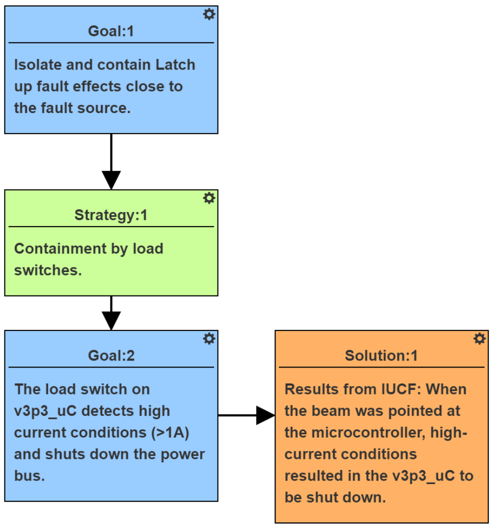
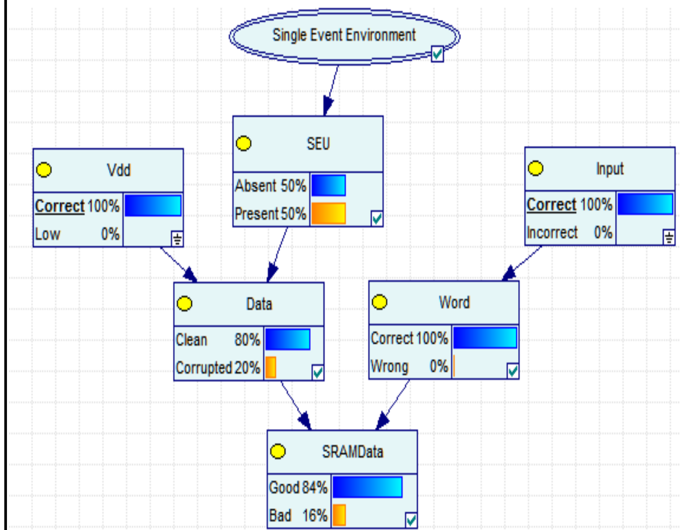
SysML	GSN	BN Network
• Specification of systems through standard notation • Added fault propagation paths	• Visual representation of argument • Goals, Strategies, and Solutions	• Nodes describe probabilities of states • Calculate conditional probabilities from observations







Radiation Reliability Assessment of CubeSat SRAM Experiment Board

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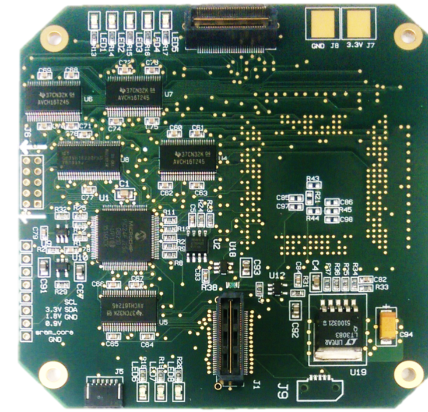
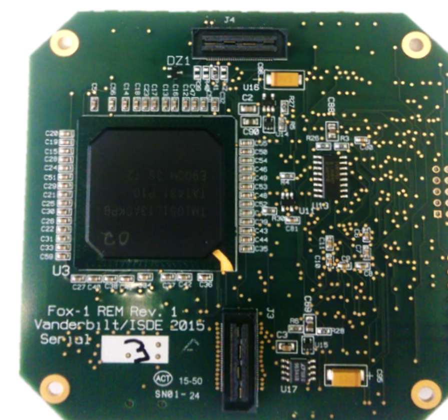
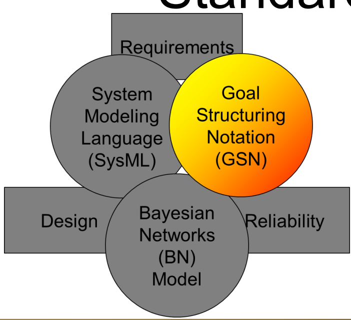
- **Assessment completed on REM**
  - 28nm SRAM SEU experiment
- **Reasons for integrated modeling**
  1. Use commercial off-the-shelf (COTS) parts
  2. System mitigation of SEL
  3. System mitigation of SEFI on microcontroller

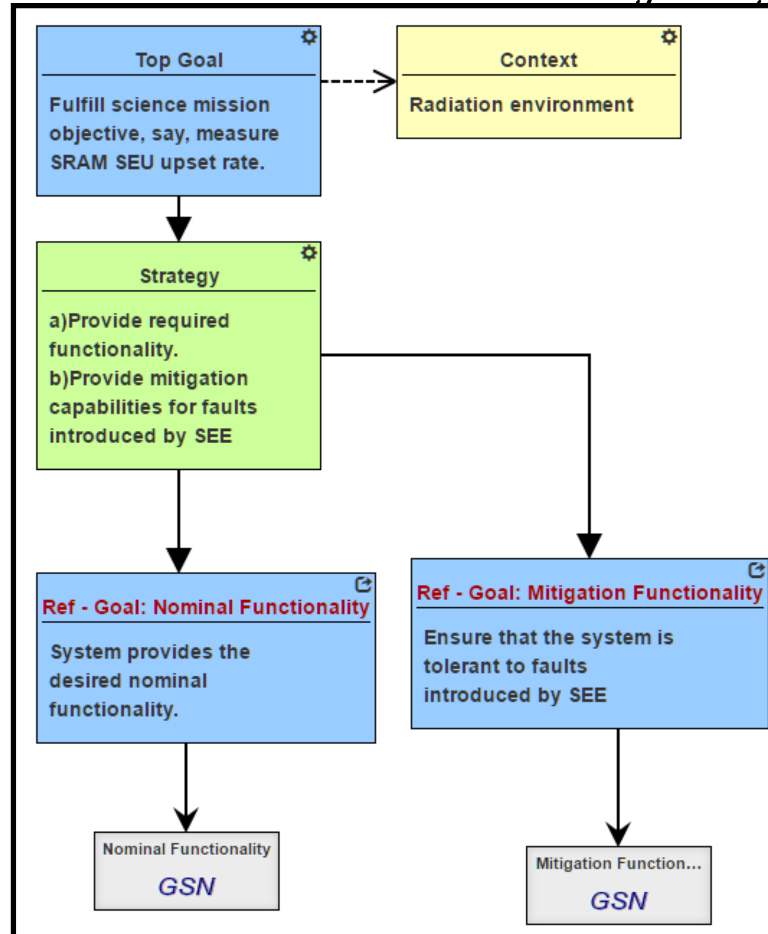




Top Level GSN Model of REM Experiment Board

- **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
  - Adapted from NASA R & M Standard





SysML Block Diagram of REM Experiment Board

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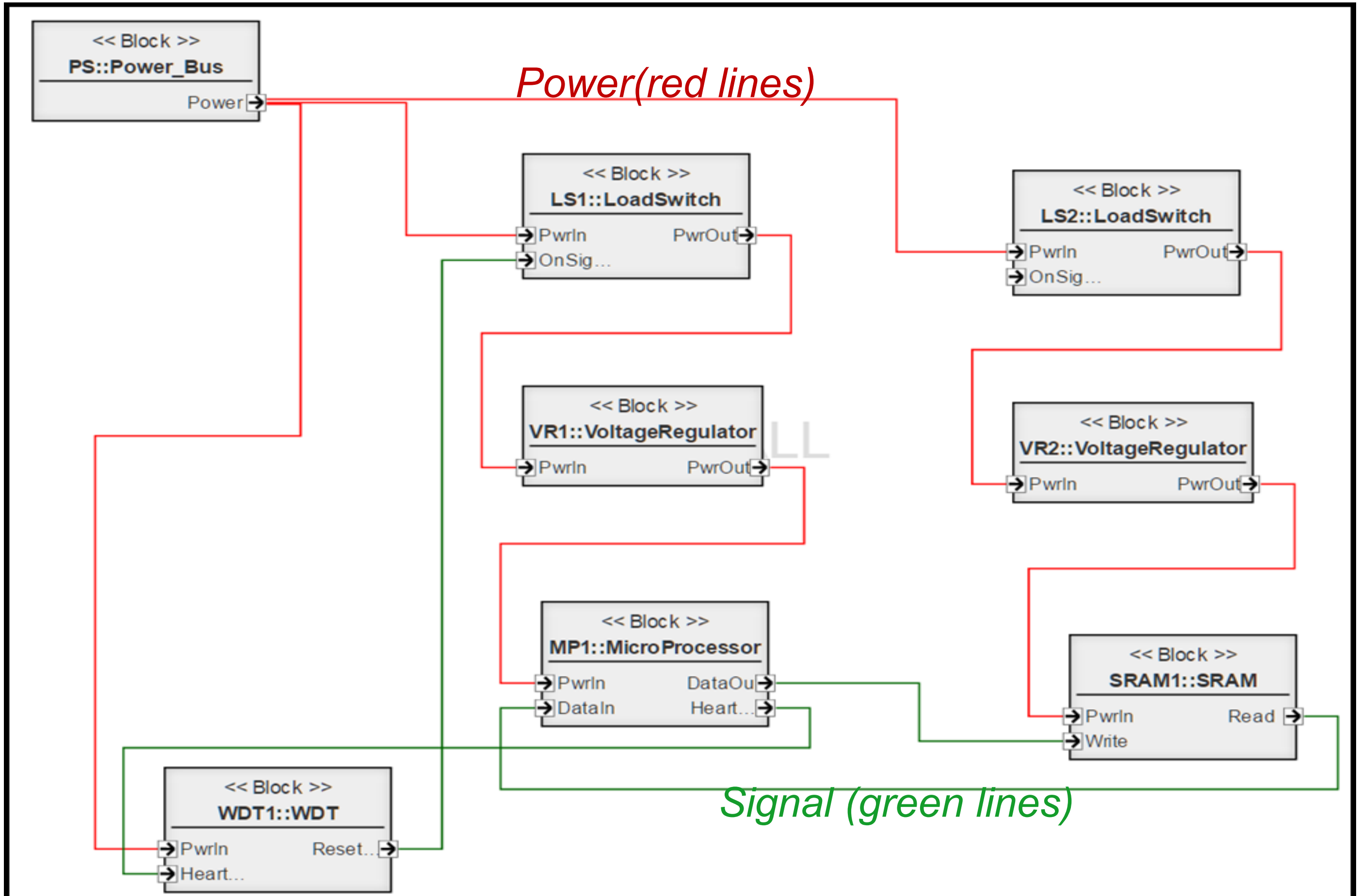

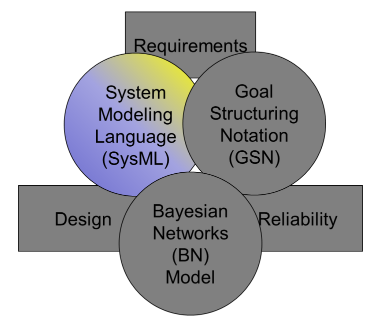

SysML Block Diagram of REM Experiment Board

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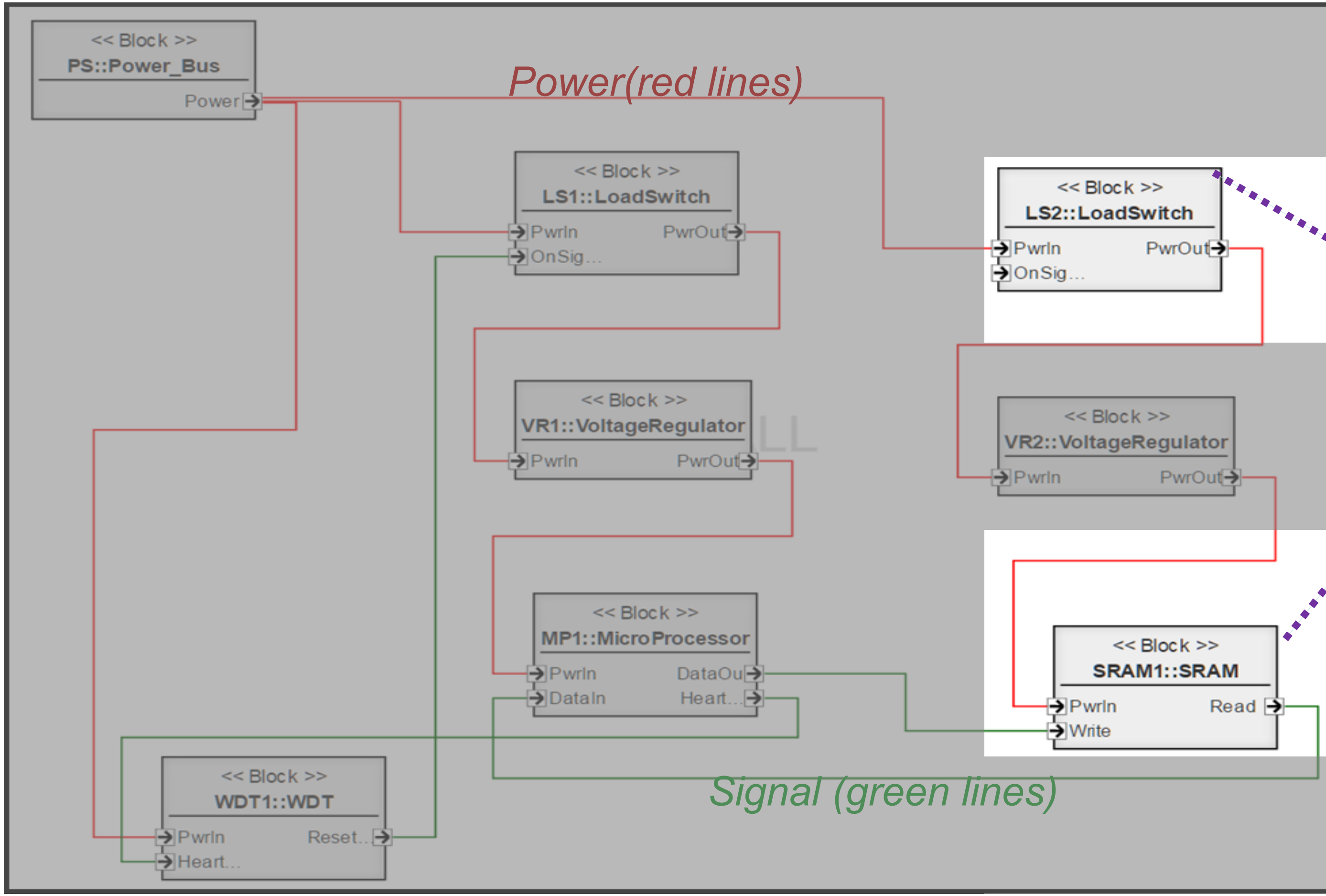
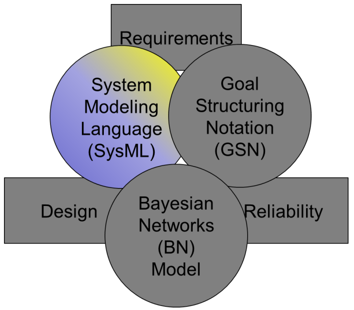


Focus on Load Switch, SRAM subsystem



SysML Internal Block Diagram with Fault Propagation Paths

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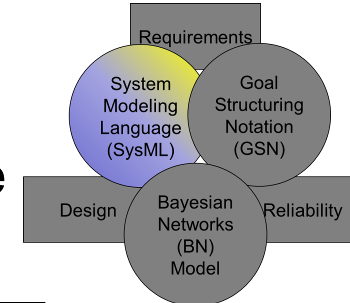
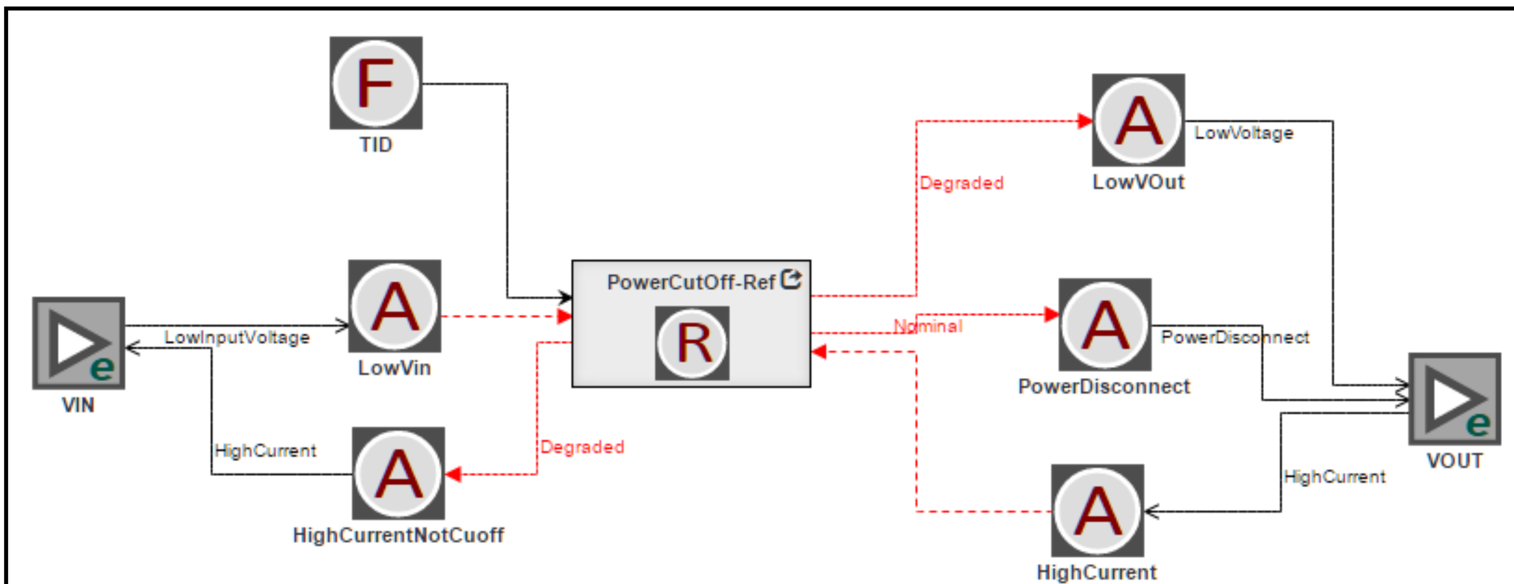


- **Load Switch**
  - Faults (F)
  - Anomalies (A)
  - Responses (R)
  - Nominal response
  - Degraded response
  - Ports



SysML Internal Block Diagram with Fault Propagation Paths

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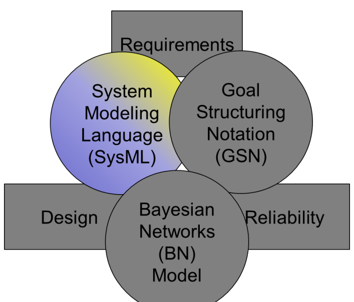
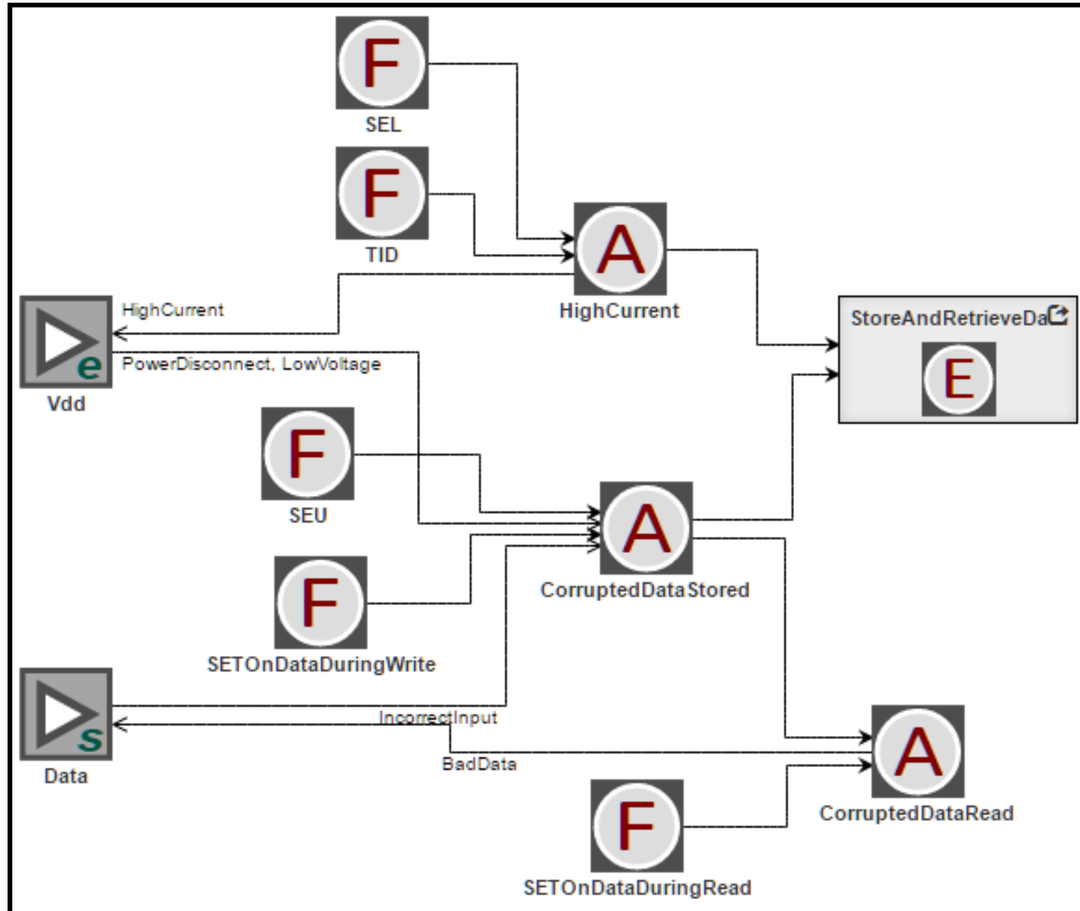
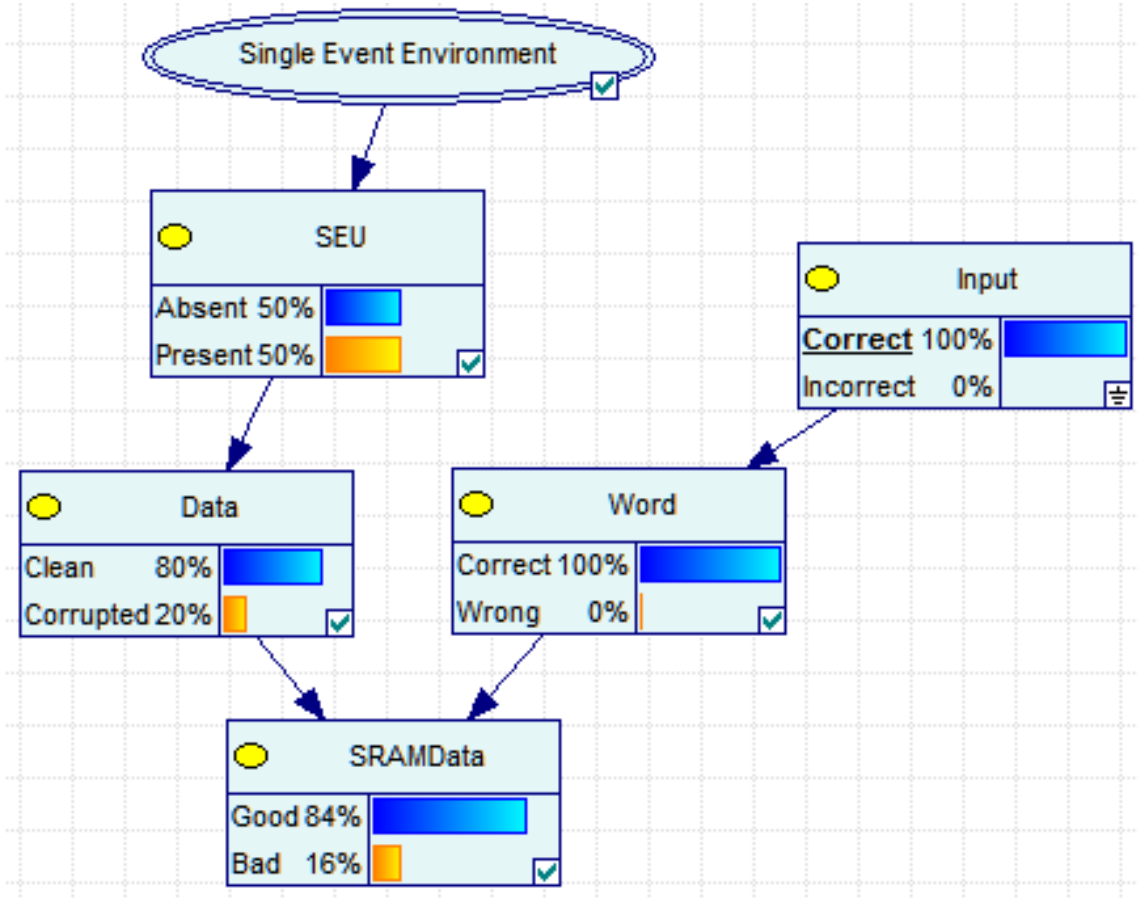
- **SRAM**
  - Effects (E)
  - Faults on different inputs

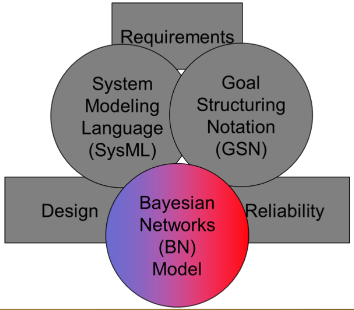




Pruned Bayesian Network Model of the REM Experiment Board

- **SEE environment set to LEO or SAA**
- **Input is data from microcontroller**
  - Assumed correct
- **Show sensitivity of SRAM data to SEE environment**





Summary

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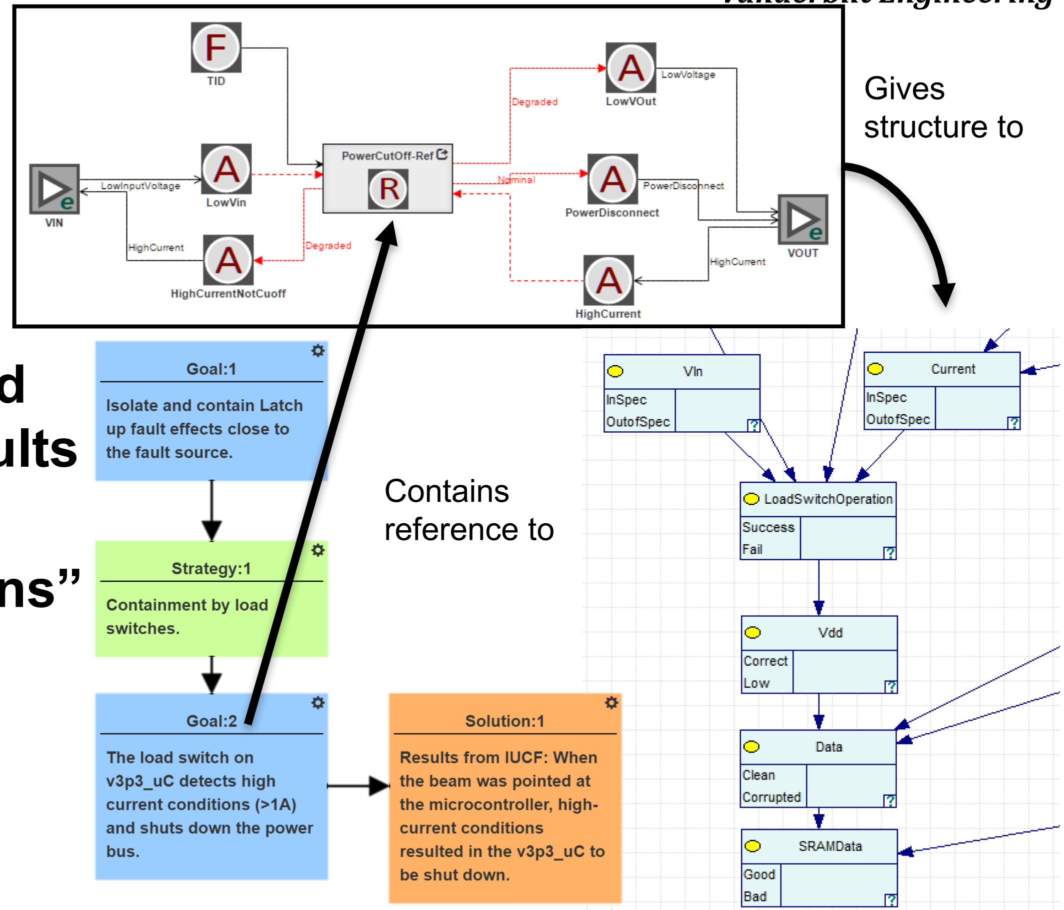
- **Developed integrated process for model-based assurance case for radiation reliability**
- **Constructed example SysML models augmented with radiation-induced faults and propagation**
- **BN inference "observations" used to assess impact of various faults on SRAM performance**



Modeling JPL Sphinx C&DH Board: Issues of Scale

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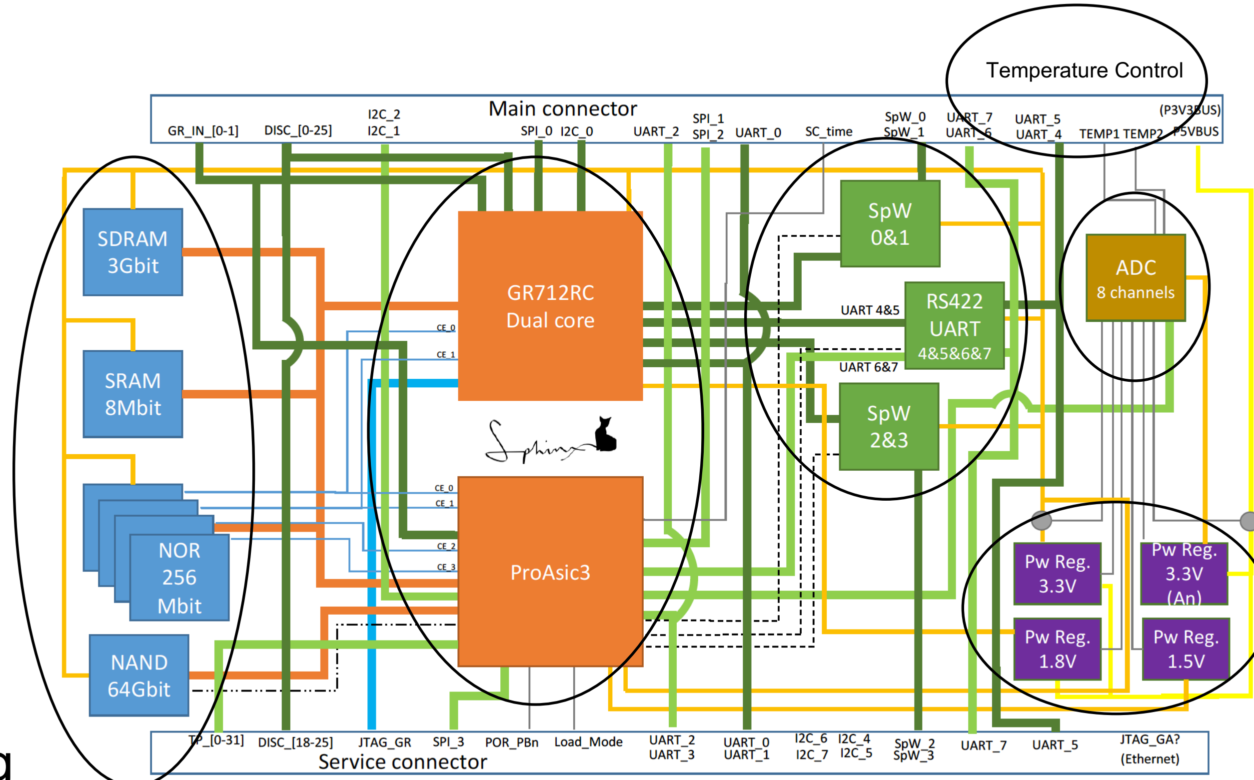
- Sphinx much more complex than Cube Sat board
- Hierarchy for managing complexity
- Schemes for categorizing sub-systems
- Subsystems based on functionality
- Components belong to more than one subsystem



Functional vs Schematic Organization Strategy

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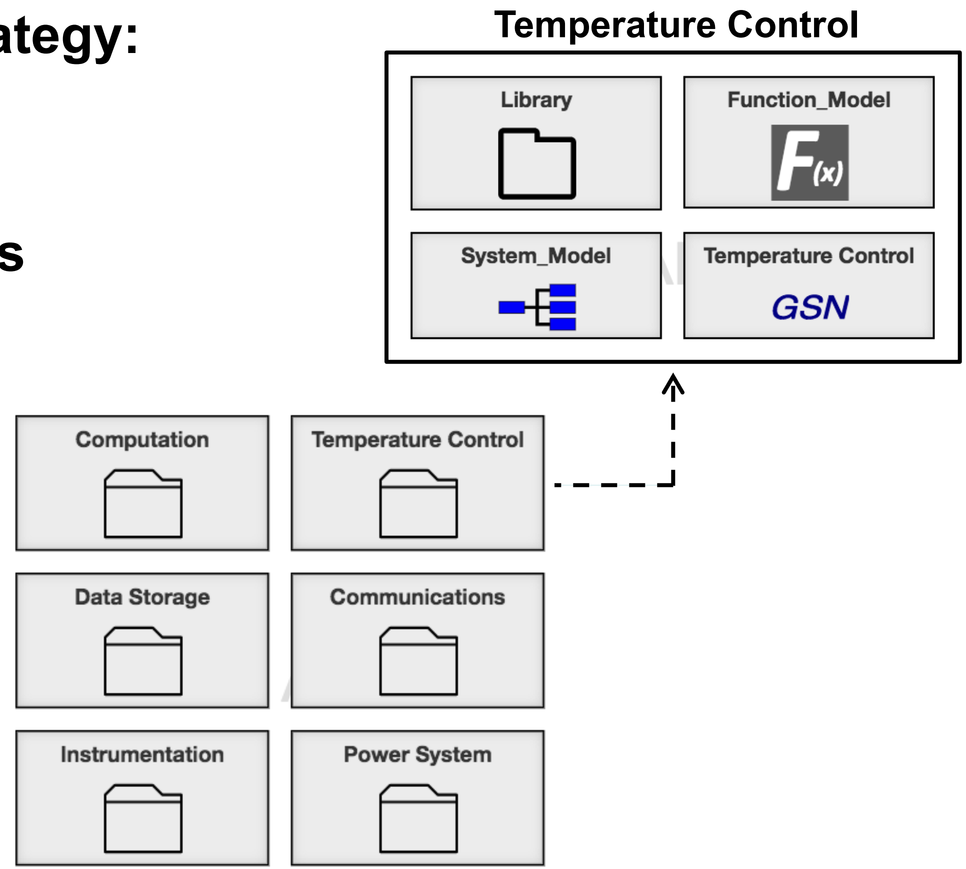
Advantages of Functional Strategy:

- Specifies purpose of components
- Simplifies functional models
- Parallels thinking of GSN arguments
- Abstraction level same as deterministic simulation

Disadvantages:

- Uses same components in multiple subsystems



GSN Radiation Parts Characterizations

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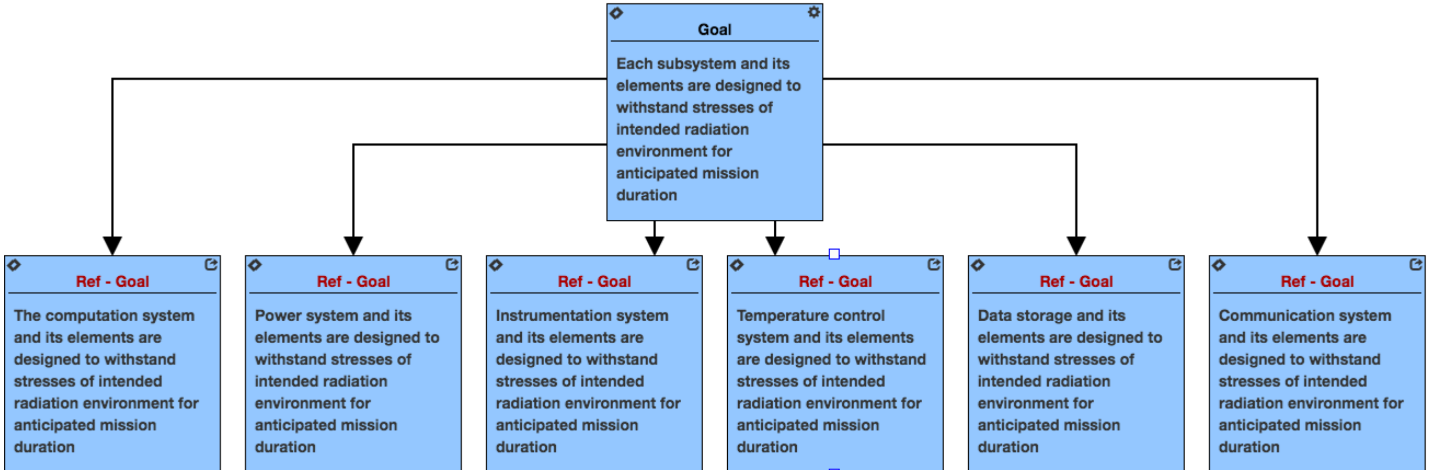

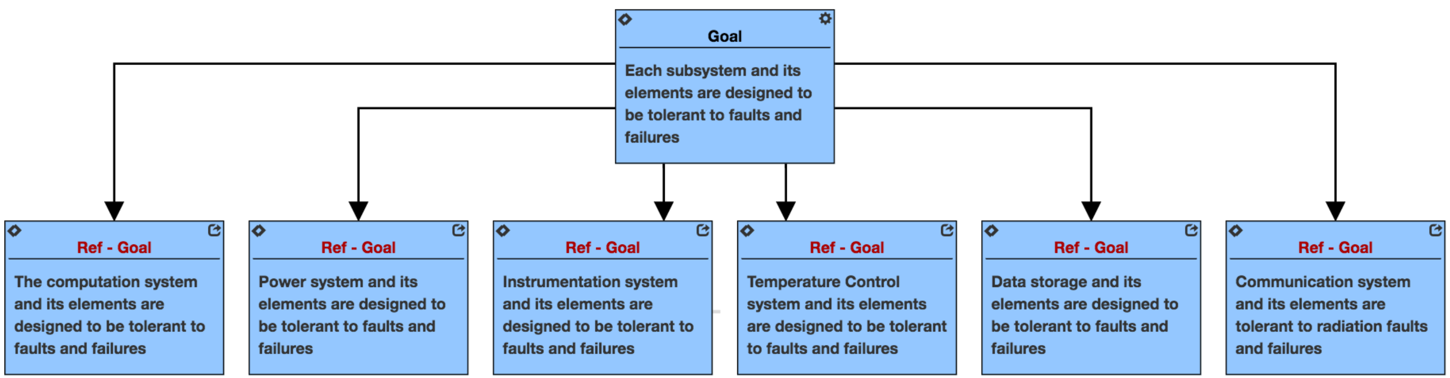

Deriving the Bayesian Net from SysML Models for the Temperature Loop Subsystem

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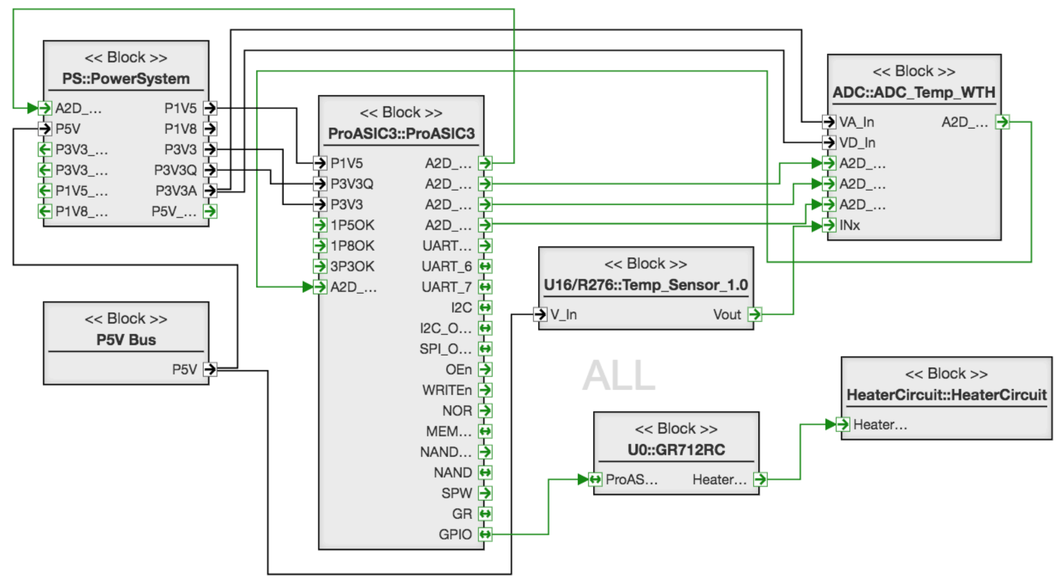
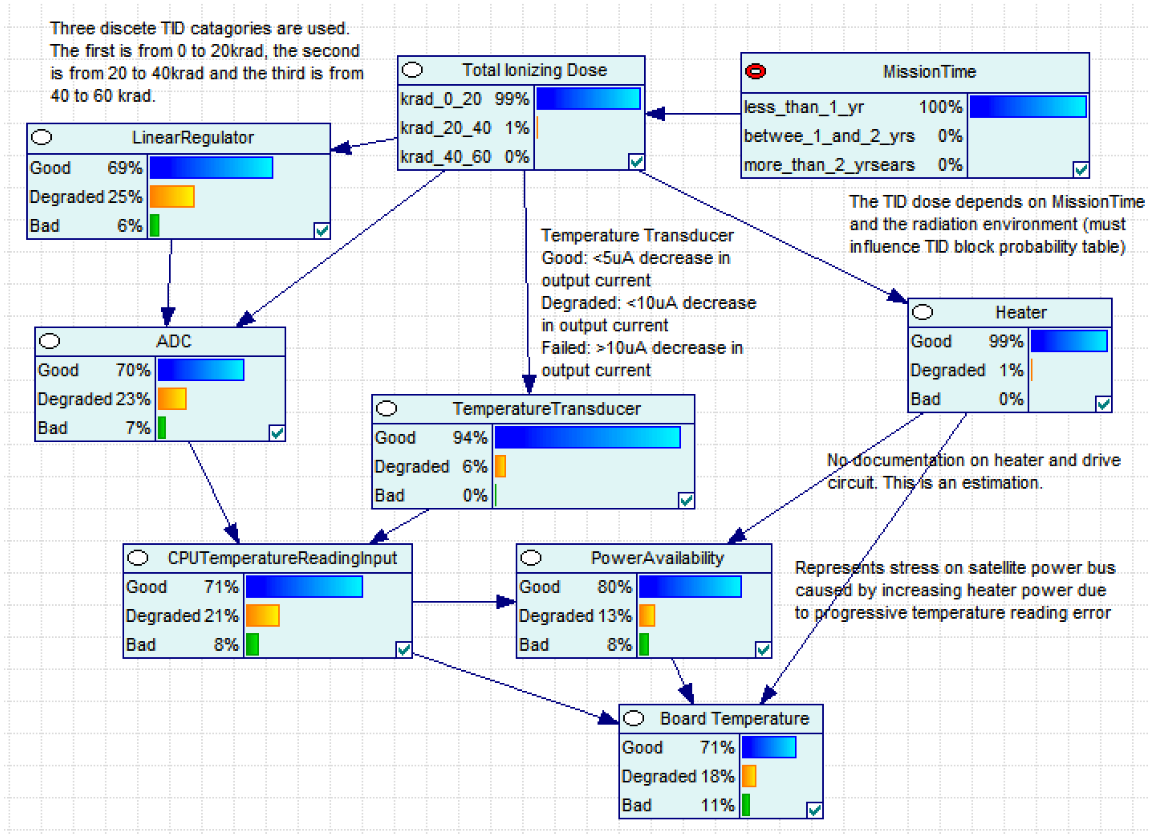
- **Block Diagram view includes all components directly involved in system functionality**
- **Links connection paths directly involved in system functionality**
- **Visualizes fault and failure propagation paths**



Temperature Control Bayesian Net

- BN only considers TID (no SELs or external faults)
- MissionTime branch sets TID
- System output is board temperature
- PowerAvailabilty node represents stress on satellite power bus due to increased heater usage
- Annotations add details and assumptions



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Jet Propulsion Laboratory
California Institute of Technology

Overview of TID and Reliability Modeling of the JPL Sphinx C&DH Board

- Arthur Witulski, P.I., Gabor Karsai, Co-P.I., Nag Mahadevan, Jeff Kauppila,
- Ronald Schrimpf, Robert Reed

JPL Sphinx C&DH Block Diagram

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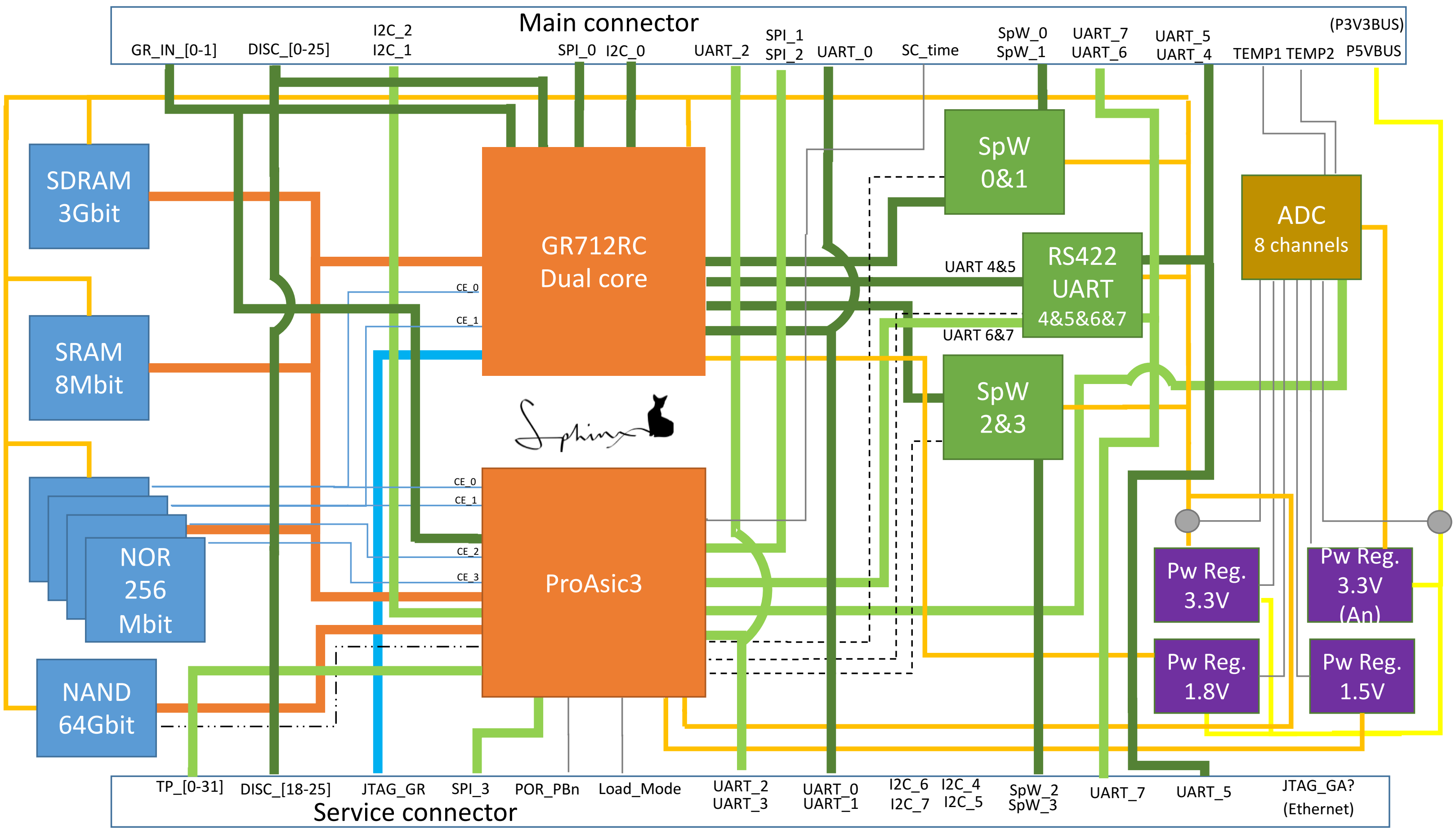

Introduction to Board Level Modeling Paradigm

- **Problem**: How to estimate impact of transistor-level degradation on system-level performance?
  - Need fast modelling turn-around time so process can be iterative
  - Must be able to accommodate many signal and part types
    - Analog-SPICE-like continuous waveforms
    - Pure digital (one-zero level)
    - Digital in the electrical domain
    - Behavioral: VHDL and Verilog AMS
    - Software: Control algorithms, etc.
  - Must be tolerant of incomplete knowledge of part performance and radiation behavior
  - Need fast run time so Monte Carlo Bayesian approach is possible

Demonstration: Temperature regulation loop model with TID Degradation

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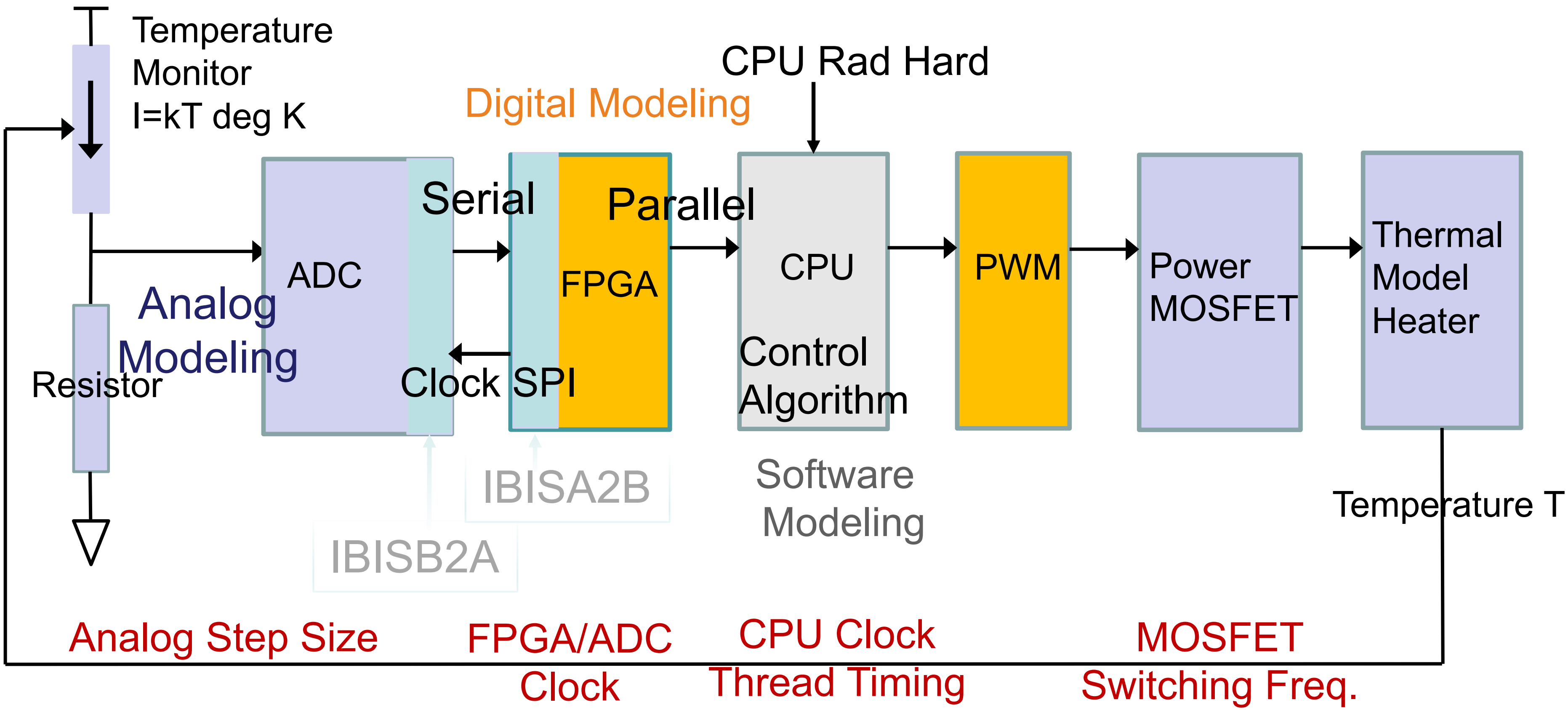
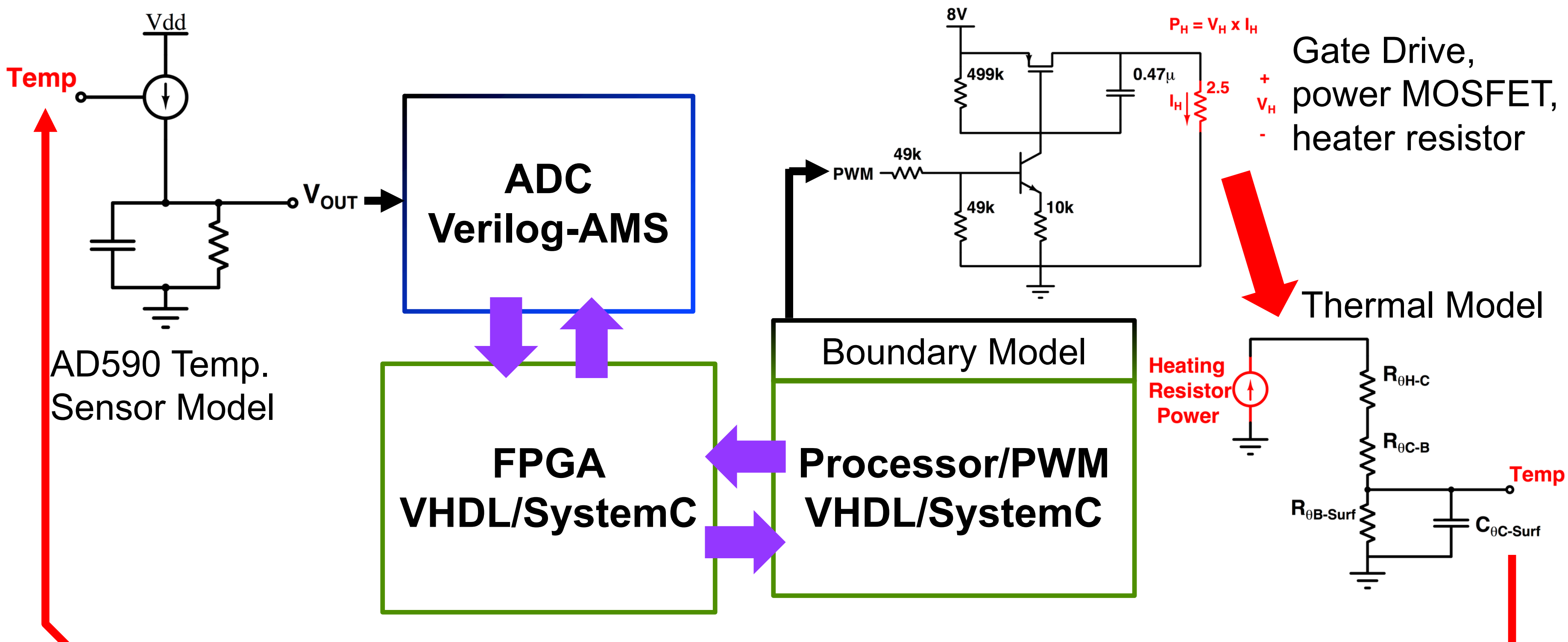


Radiation modeling embedded in parameter variation

Mentor Questa and SystemC

- The Questa ADMS simulation package from Mentor Graphics is the simulation engine within the Expedition PCB design flow
  - Capable of co-simulating SPICE, Behavioral (Verilog, Verilog-AMS, VHDL, VHDL-AMS), and SystemC
  - Synchronization of time steps and convergence routines
- Questa's ability to simulate models from multiple hierarchy levels provides the capability to model a complex system
  - Accurate and detailed transistor level models (Temp Sensor)
  - IBIS models at digital interfaces for signal integrity
  - Behavioral level models for complex circuits (ADC, FPGA, etc.)
- We have successfully simulated behavioral models, IBIS models, Spice models and SystemC within one netlist and transient simulation

Temperature Regulation Loop – Questa ADMS



- **The temperature regulation loop is closed**

Questa ADMS Simulation Results - Temperature

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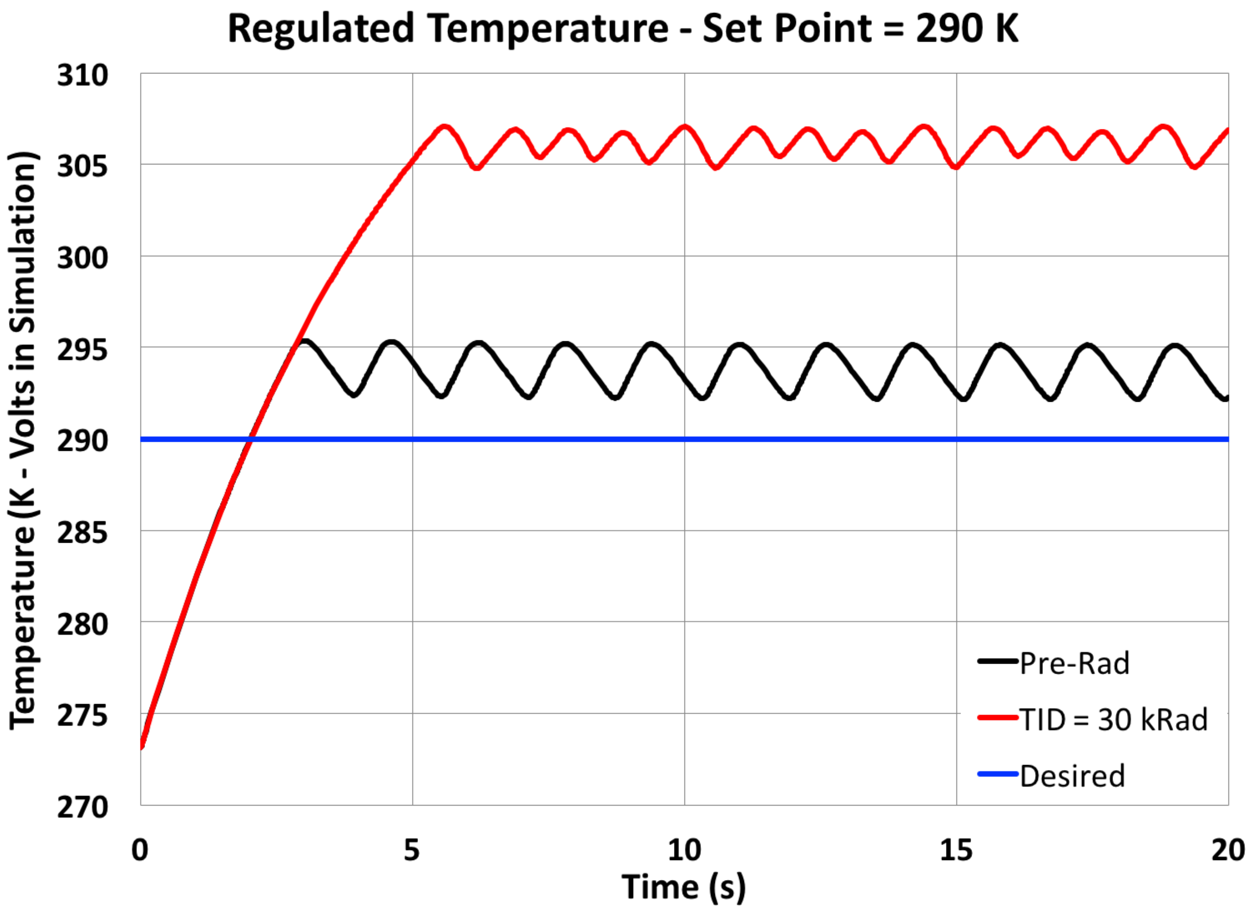

Fast simulation time ~20 sec

Set point = 290 K

Degraded models show significant impact on temperature profile

Continuous Bayesian Network (BN) Model

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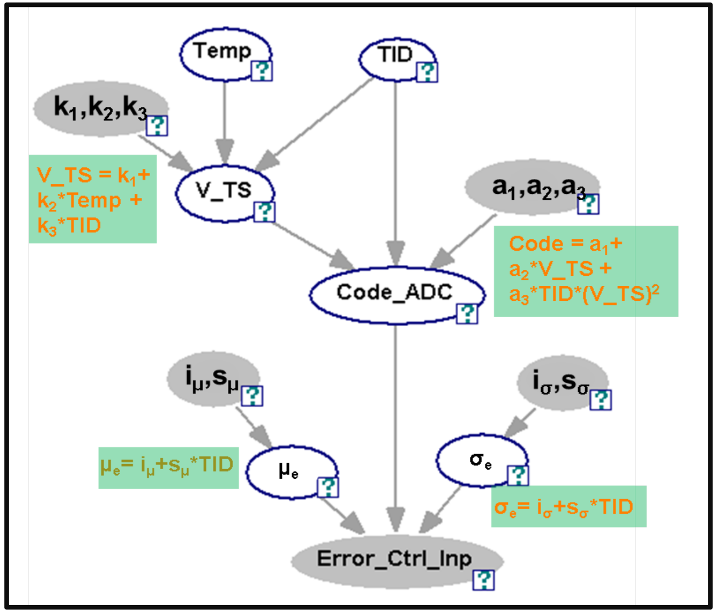

Legend

x -- **Stochastic node – X= Gaussian(μ,σ)**

y -- **Deterministic node (V_TS, Code, μ_e ,σ_e)**
Root Nodes with Uniform priors (Temp, TID)

Eqn. -- **Likelihood Function for deterministic nodes**

BN Model (PyMC code)

- BN Nodes → Domain Variables and function parameters.
- Relationship between Nodes → Likelihood functions.

BN Setup/ Observations (Test bench data)

- Initialize parameter nodes with (prior) probability distributions.
- Associate evidence (data) with appropriate BN nodes.

BN Execution

- Markov Chain Monte Carlo sampling algorithms sample prior distributions and evaluate outputs (likelihood functions).
- Iterate until predictions converge to observed data.

BN Results

- Posterior *(updated)* distribution for each node.
- Use posterior distributions of parameters to get an estimation of the spread (distribution) in domain variables such as
  - *Output voltage of temperature sensor (V_TS)*
  - *Output code from ADC (Code_ADC)*
  - *Error in input to controller (Error_Ctrl_Input)*

Continuous Bayesian Network Results

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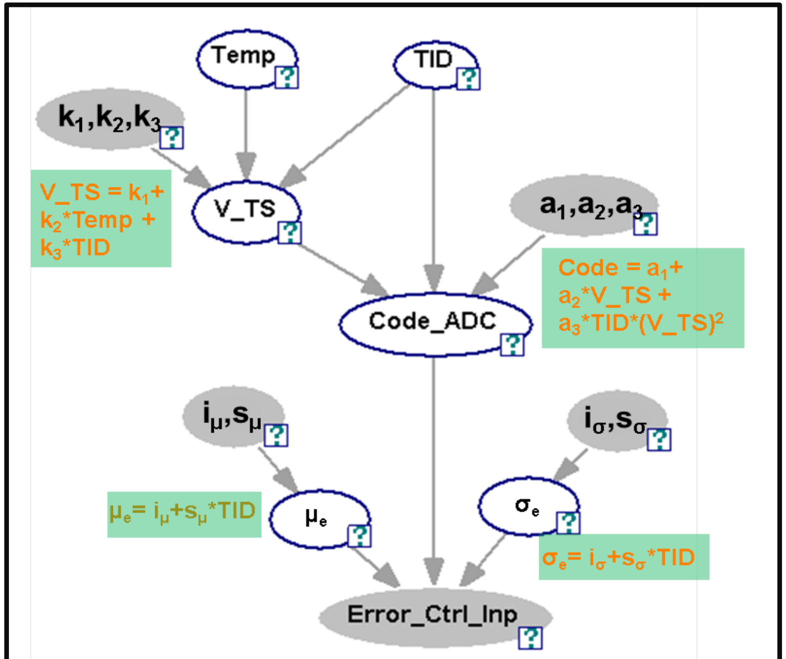

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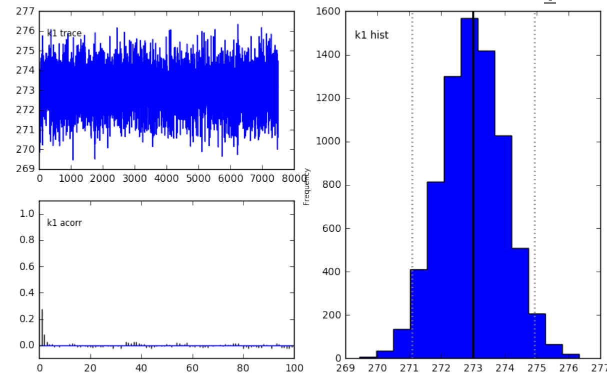
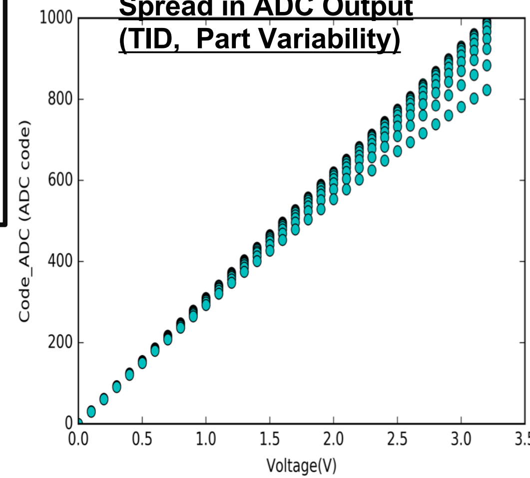
Eqn. -- Likelihood Function for deterministic nodes

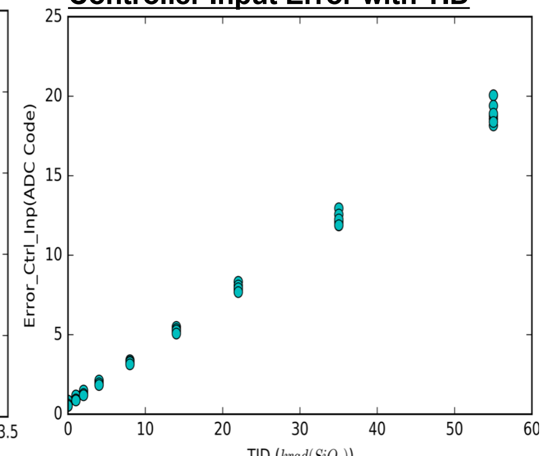
Posterior Distribution (parameter k_1)



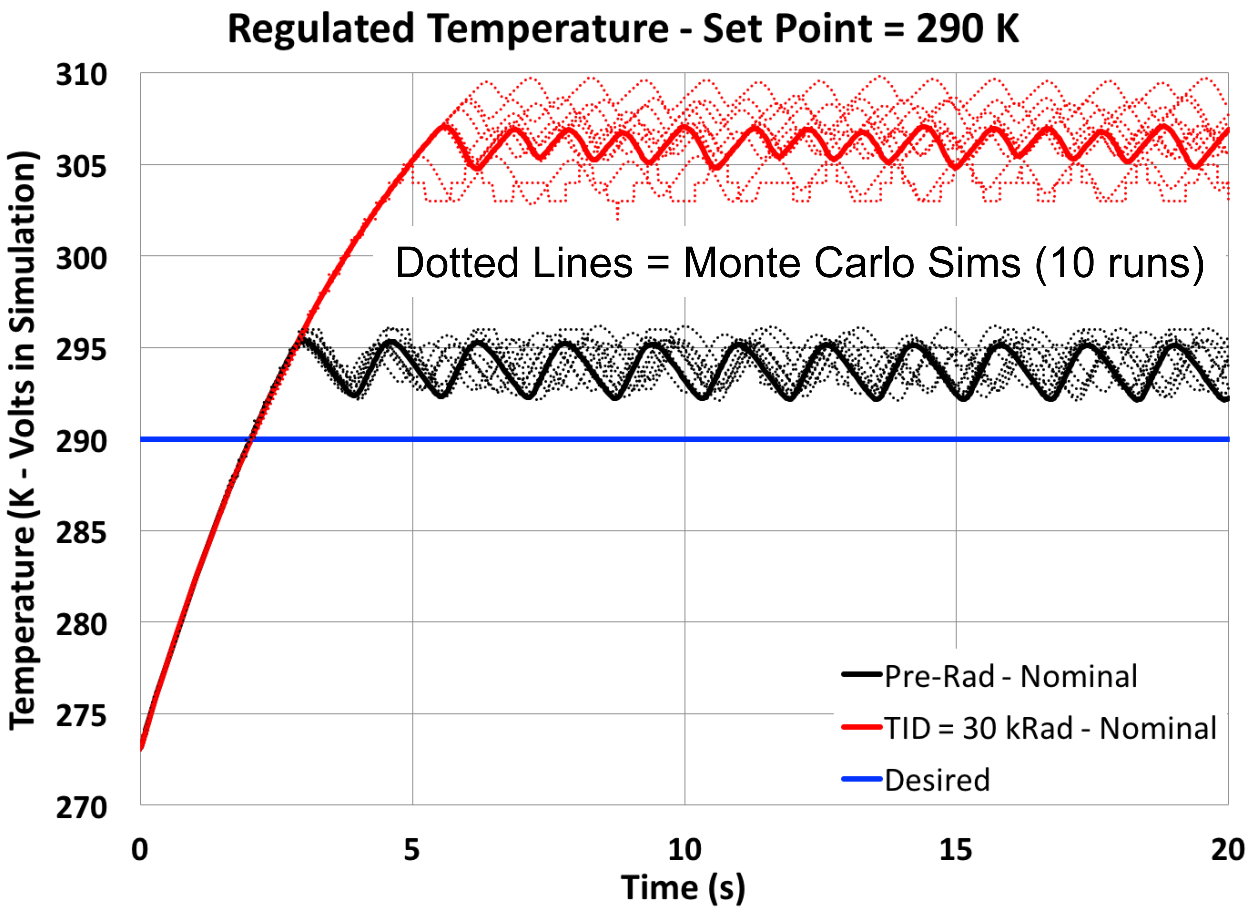
Spread in ADC Output (TID, Part Variability)



Controller Input Error with TID



Questa ADMS Sim Distributions Electrical and Radiation Parameters



Set point = 290 K

Monte Carlo analysis of the circuit with Pre-Rad and 30 kRad component models

Black shows component variations pre-rad

Conclusions

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- Board-level modeling requires simulation of **analog**, **mixed-signal**, and **fully digital components**, as well as **software**
- Created modeling and simulation paradigm for a fully capable, multi-domain board simulator using Mentor Questa with SystemC
  - Shows the impact of component-level variations on board-level system parameters
  - Fast run times for long simulation clock times
  - Fully customizable abstraction levels from software to all-digital to behavioral models to Spice-like circuit simulation
  - Compatible with other Mentor products like circuit board layout and parasitic tools
  - Parameter variation and Monte Carlo simulation capability
- Simulation demonstrates significant impact on the system-level variable (Temperature) owing to TID degradation of ADC and sensor
- Clear road map for next steps in C&DH radiation modeling