SAND2019-0612C

Sandia National Laboratories

How MBSE is Reducing the Duration of the Nuclear Weapon Development Lifecycle

PRESENTED BY

Anthony Matta – Manager, Model Based Systems Engineering

- Casey Noll
- Erik Olson
- Ryan Coleman

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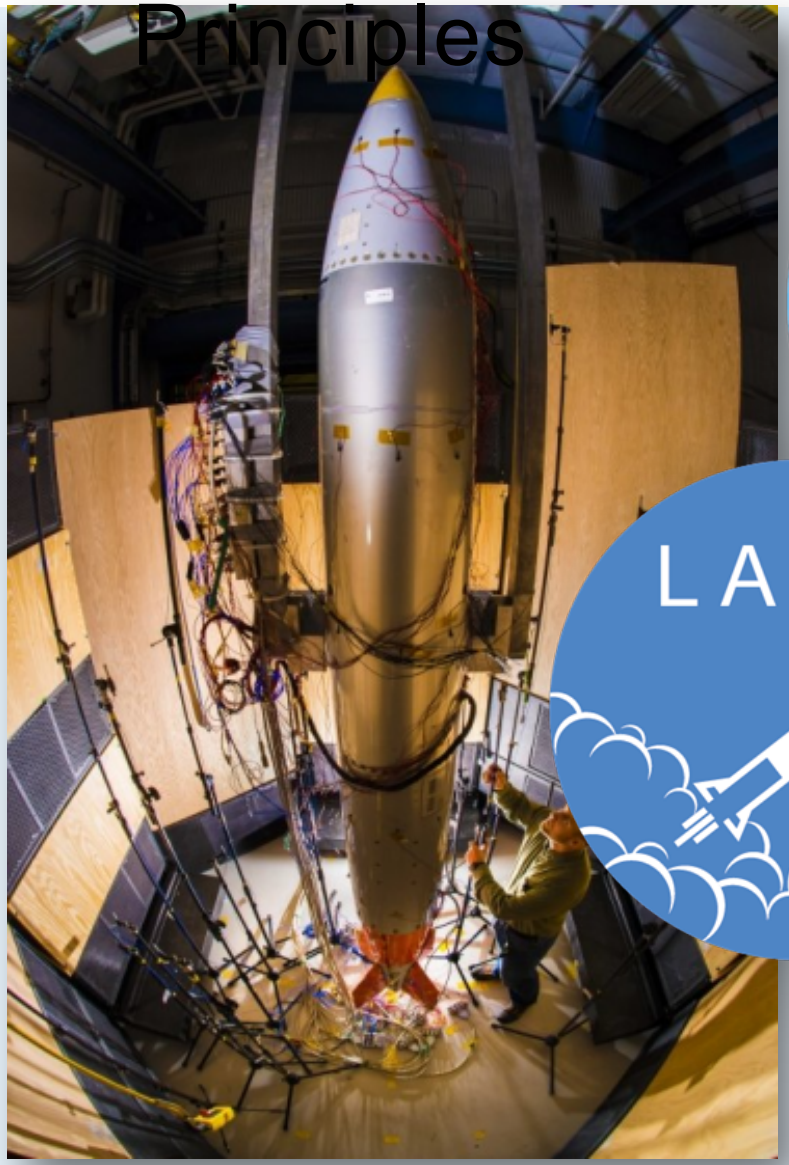
Sandia National Laboratories (SNL) Enterprise Pillars

Current Stockpile, Nuclear Triad, & Design Principles



ALWAYS perform when intended

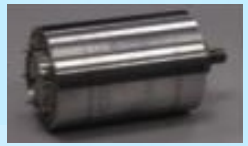
NEVER at any other unapproved time

Unique Nuclear Weapon Activities

Warhead systems engineering & integration

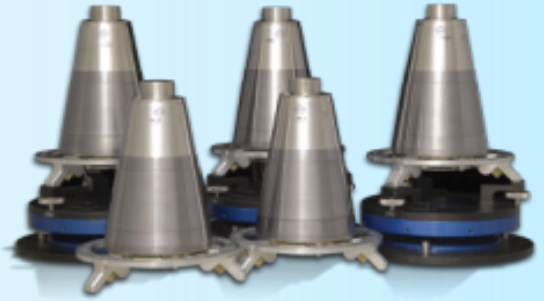
Design agency for Non-nuclear components

Safety systems

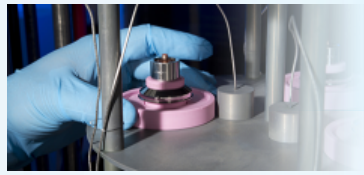


Gas transfer systems

Radar



Arming, fuzing & firing systems



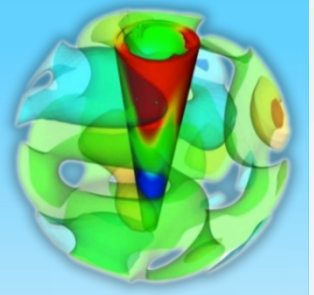
Neutron generators

Multi-disciplinary capabilities required for design, qualification, production, surveillance, experimentation/computation

Major environmental test facilities & diagnostics

Materials Science

Light initiated high explosive

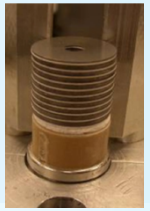


Computational analytics

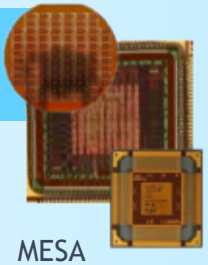
Production agency

Neutron generators

Sandia External Production



Thermal battery back up



MESA microelectronics

Phase 6.X Process for NW Product Realization Lifecycle

Rapidly respond to emerging deterrence needs

Field an appropriate response to a high-confidence assessed threat before Initial Operating Capability of that threat.

Agree upon the appropriate response to a technological surprise within **three months** of discovery.

Perform Phases 2 through 5 within **three years** of a new weapon authorization from the Nuclear Weapons Council.

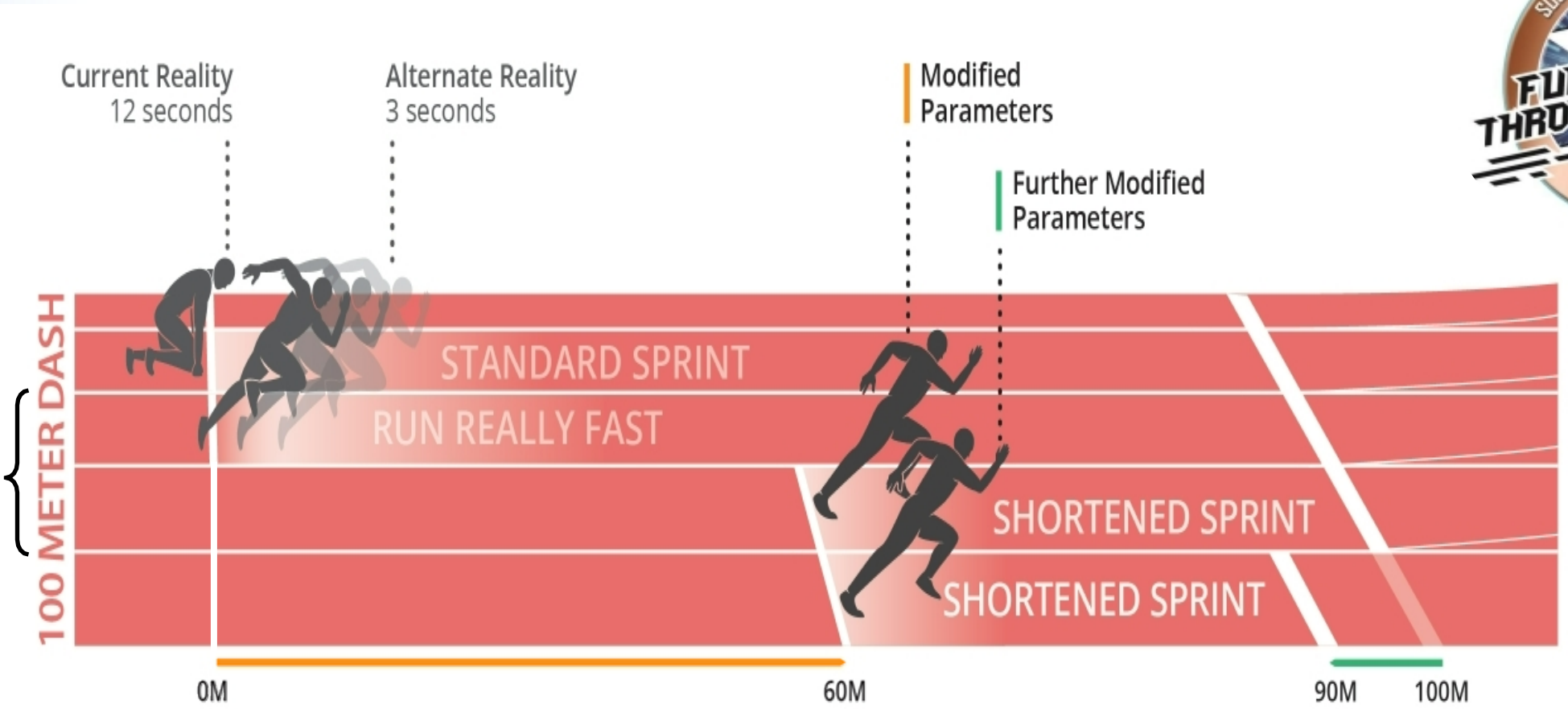
Complete full production cycle for each new weapon within **two years**.

Draft Goals and Ends for the Nuclear Security Enterprise (NSE)

1. Reduce **Time** to Perform a Life Extension Program.
2. Field an Inherently **Safe and Secure** Stockpile.
3. Improve Stockpile **Affordability**.
4. Improve NSE **Agility** and Resiliency.
5. Improve NSE's **Ability to Respond** to Anticipated Mission Requirements.

Strategy

Two methods toward achieving the dramatic speed up:

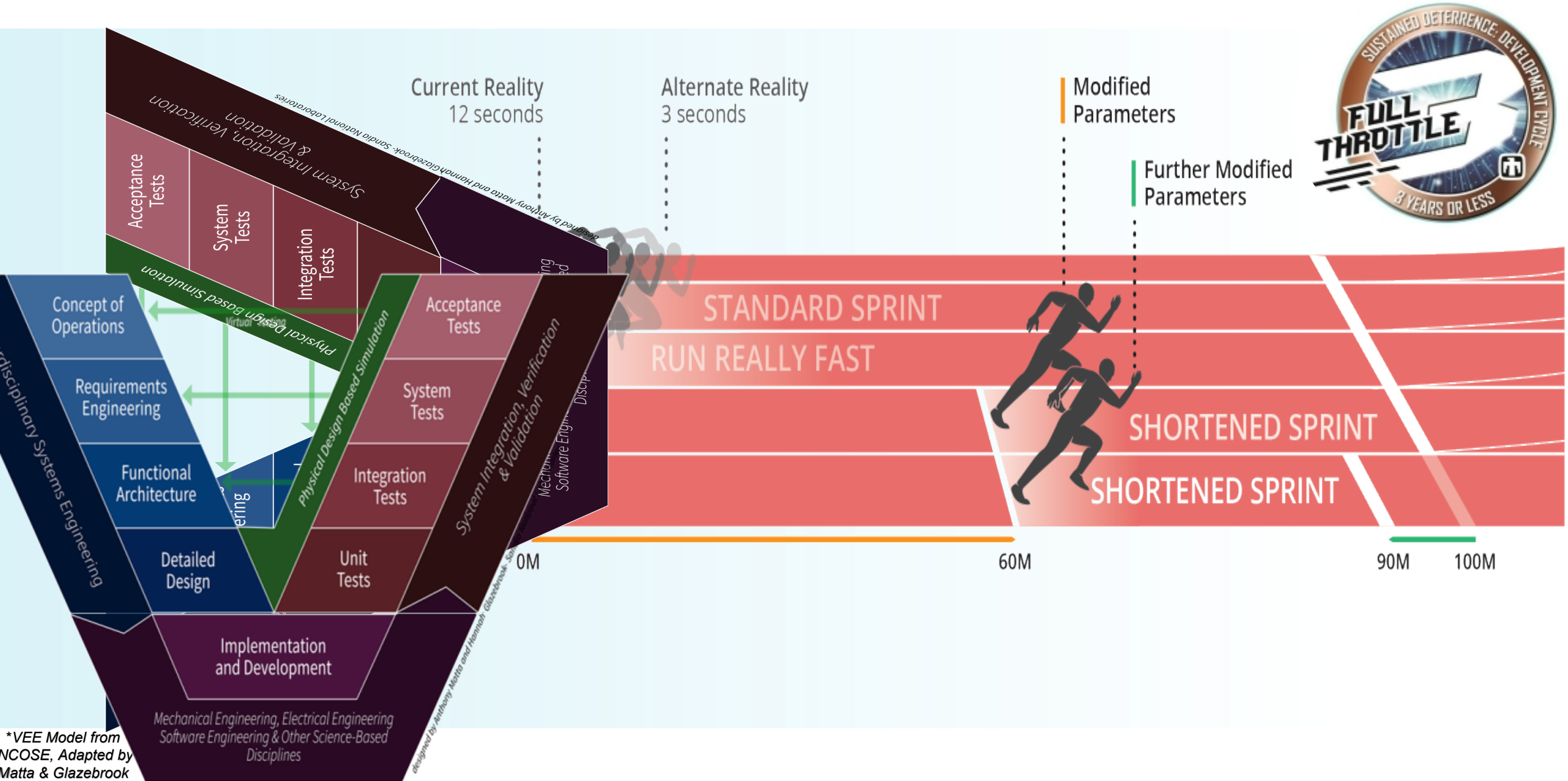


Move the starting line by building infrastructure

- Model-based approaches with reference architectures
- Common testers
- Design libraries
- Component reuse
- Modular architectures

May shorten the required distance by possibly performing some qualification after FPU

Strategy



*VEE Model from NCOSE, Adapted by Matta & Glazebrook

Focus Area Representatives

NW DESIGN LIFECYCLE FOCUS AREAS

Current Cycle Time
~12 Years

AND

Casey Noll

- Verification & Validation MBSE
- Complex testing and environment reference architectures

Erik Olson

- Reduced order modeling
- Interrelating high fidelity physics codes for early design engineering

Ryan Coleman

- Digital Twin data strategy for integrated models
- Ontologically based integrated data sets

AND

Objective Cycle Time
<3 Years

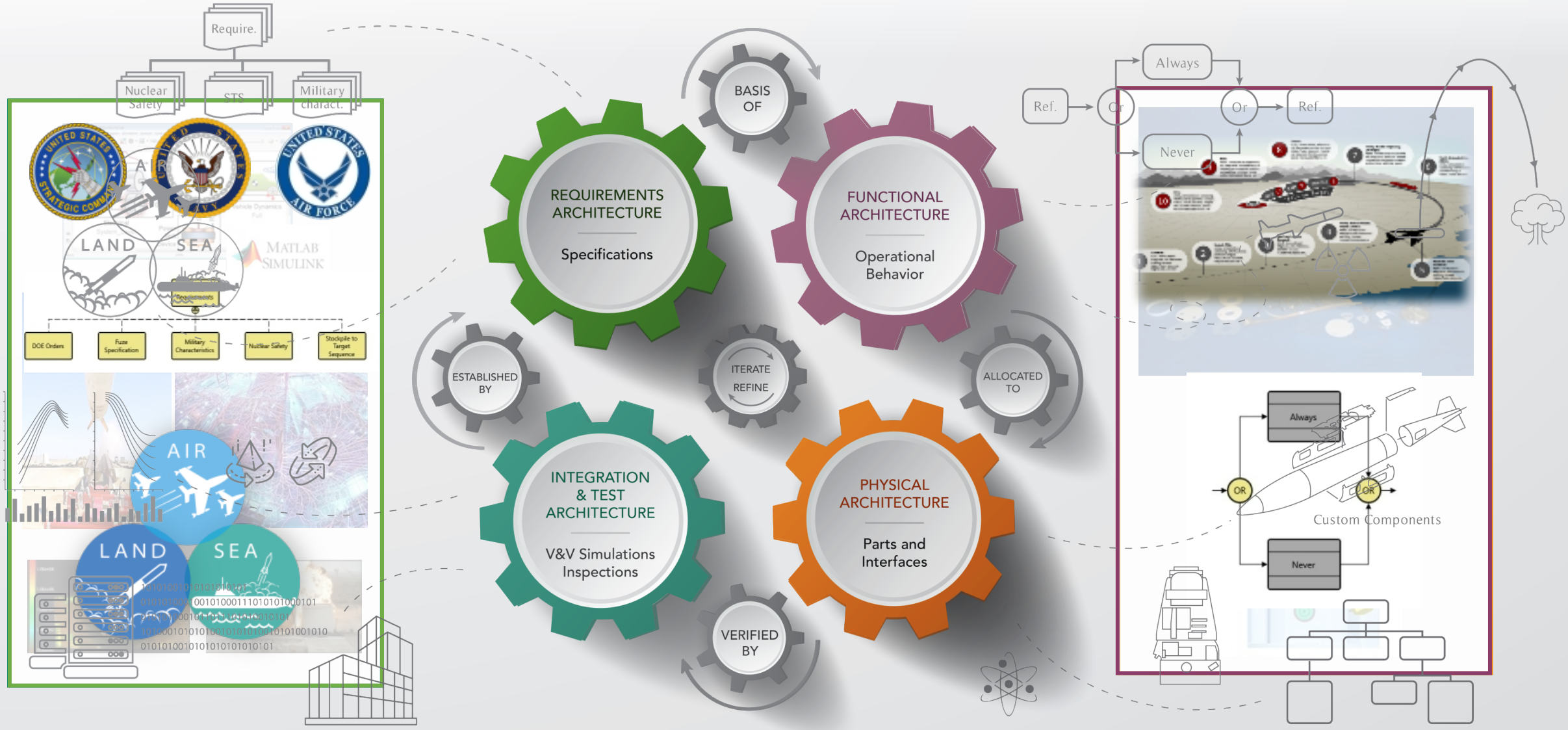
How Modeling Verification and Validation Activities Reduce the NW Development Time

Casey Noll

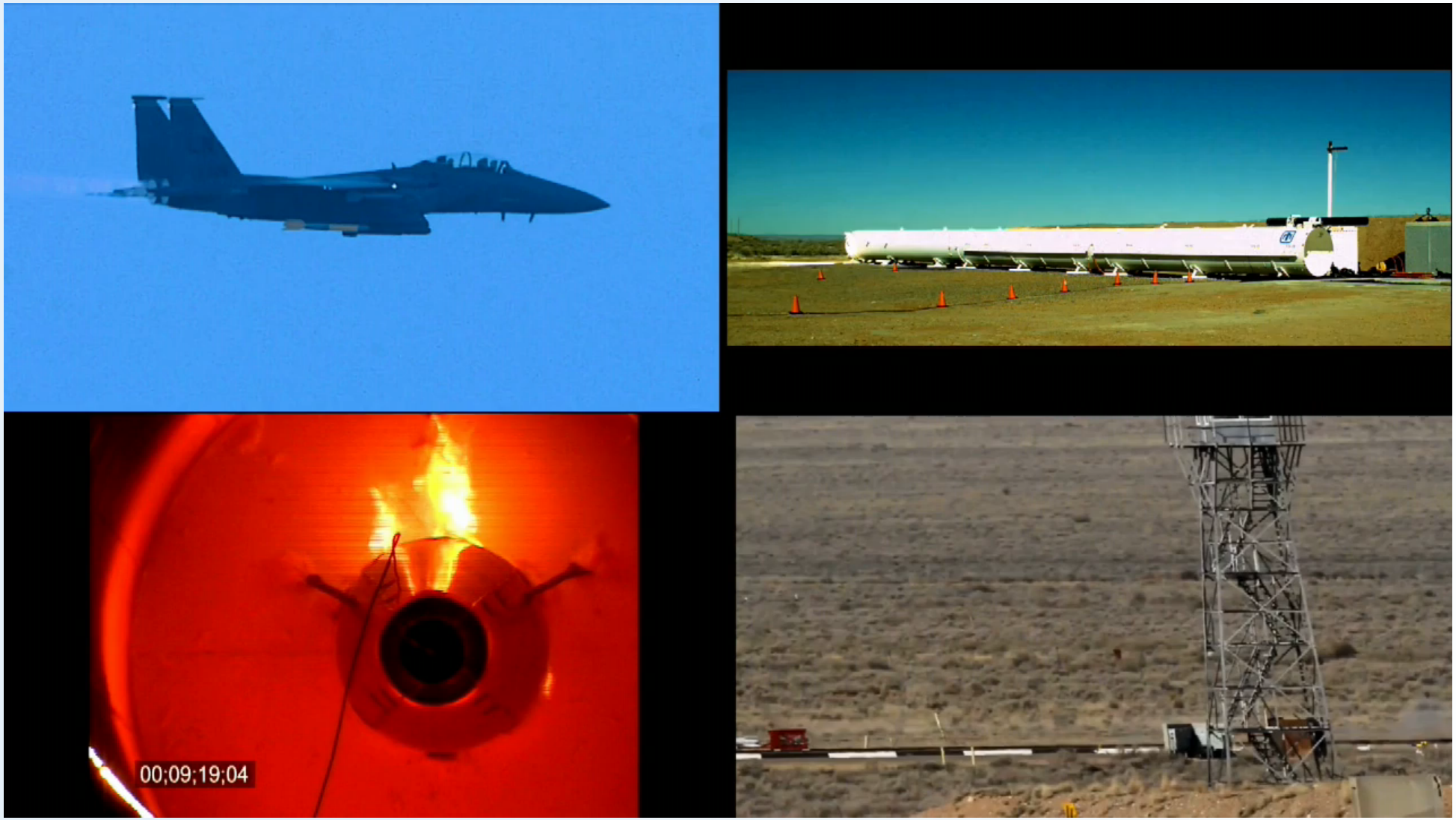
R&D Systems Engineering

Served as a Nuclear Weapon (NW) component Product Realization Team (PRT) Lead responsible for the development and transition to production of custom high reliability components supporting multiple programs impacting the NW stockpile. Casey has his BS/MS in Engineering Management, from Missouri University of Science and Technology and is currently pursuing his Master in Systems Engineering from Stevens Institute of Technology.

MBSE for Nuclear Deterrence

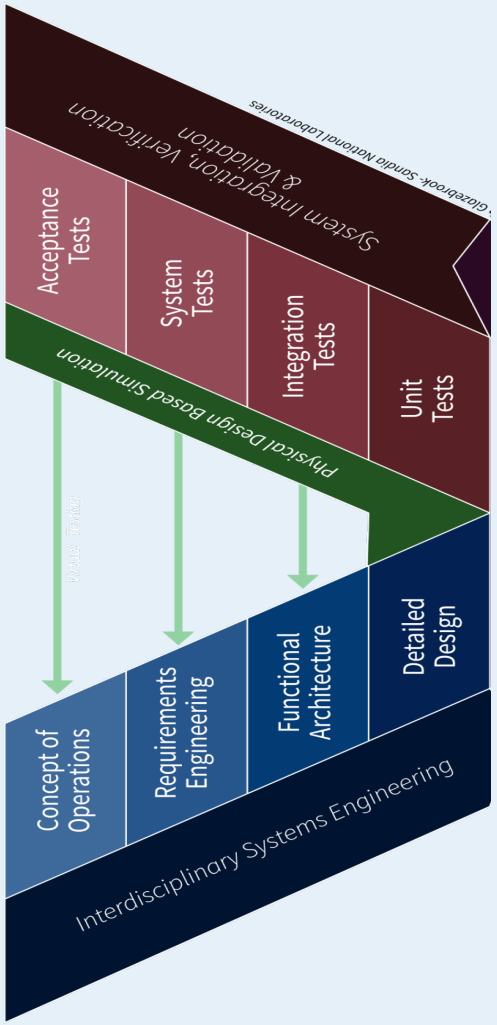


Verification & Validation



How can V&V modeling contribute to reducing the lifecycle for NW?

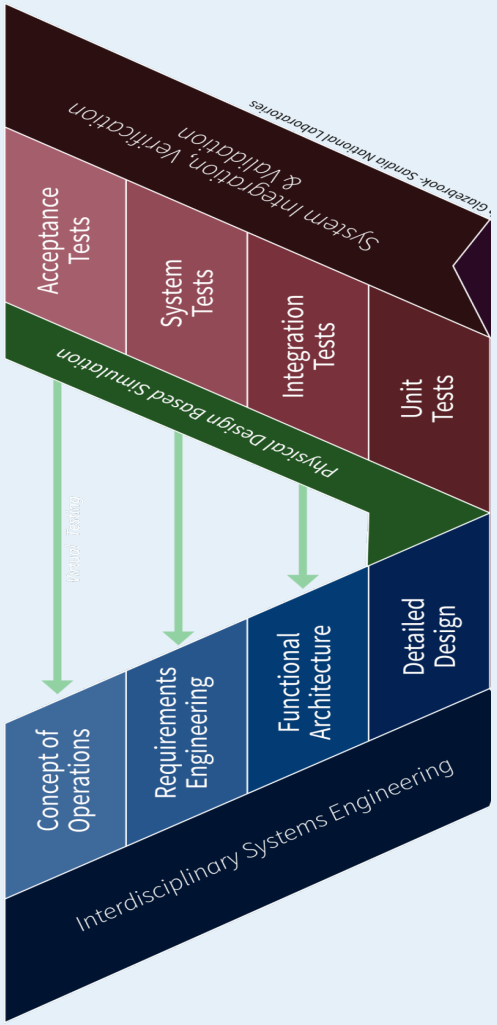
Verification & Validation

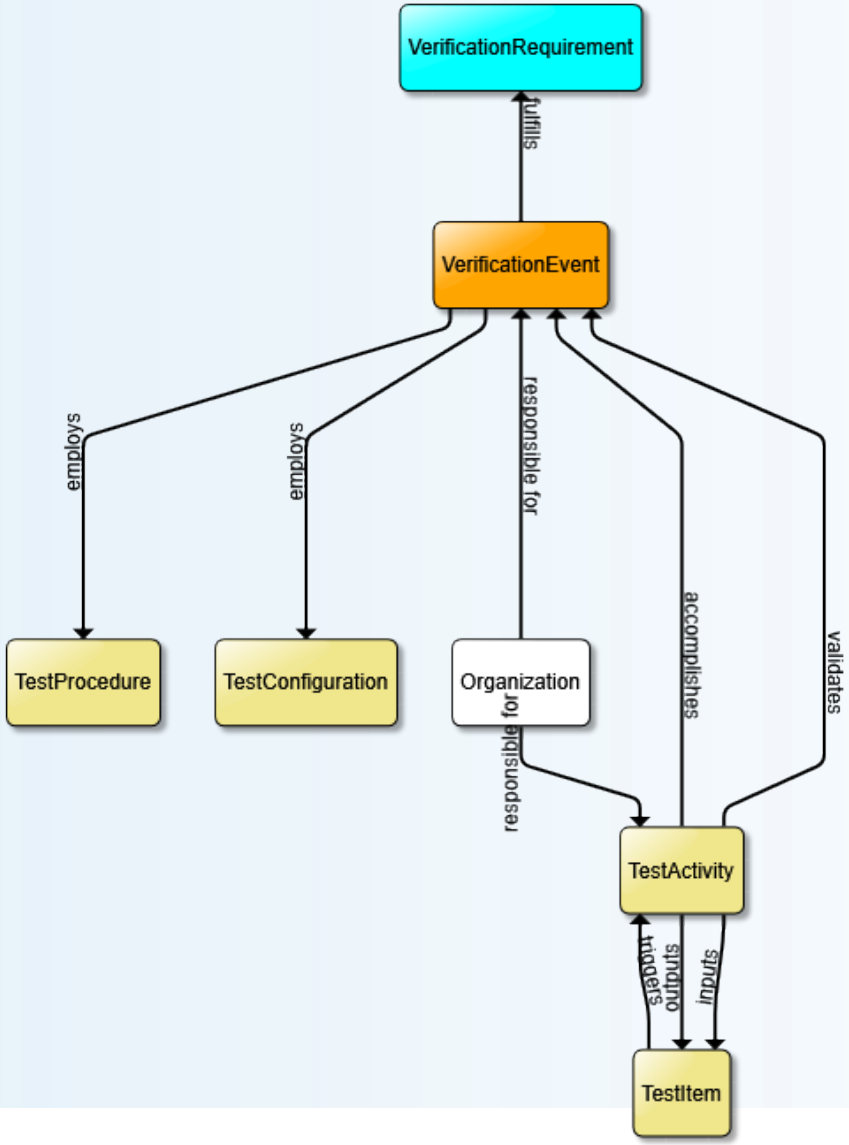


Requirement No.	Document	Paragraph	Shall Statement	Verification Success Criteria	Verification Method	Facility or Lab	Phase[a]	Acceptance Requirement?	Preflight Acceptance?	Performing Organization	Results
Unique identifier or each requirement	*Document number the requirement is contained within*	*Paragraph number of the requirement*	*Text (within reason) of the requirement, i.e., the "shall"*	*Success criteria for the requirement*	*Verification method for the requirement (analysis, inspection, demonstration, test)*	*Facility or laboratory used to perform the verification and validation.*	*Phase in which the verification and validation will be performed.*	*Indicate whether this requirement is also verified during initial acceptance testing of each unit.*	*Indicate whether this requirement is also verified during any pre-flight or recurring acceptance testing of each unit*	*Organization responsible for performing the verification*	*Indicate documents that contain the objective evidence that requirement was satisfied*
P-1	xxx	3.2.1.1 Capability: Support Uplinked Data (LDR)	System X shall provide a max. ground-to-station uplink of…	1. System X locks to forward link at the min and max data rate tolerances 2. System X locks to the forward link at the min and max operating frequency tolerances	Test	xxx	5	Yes	No	xxx	TPS xxxx
P-i	xxx	Other paragraphs	Other "shalls" in PTRS	Other criteria	xxx	xxx	xxx	Yes/No	Yes/No	xxx	Memo xxx
S-i or other unique designator	xxxxx (other specs, ICDs, etc.)	Other paragraphs	Other "shalls" in specs, ICDs, etc.	Other criteria	xxx	xxx	xxx	Yes/No	Yes/No	xxx	Report xxx

Source: NASA Systems Engineering Handbook

Verification & Validation





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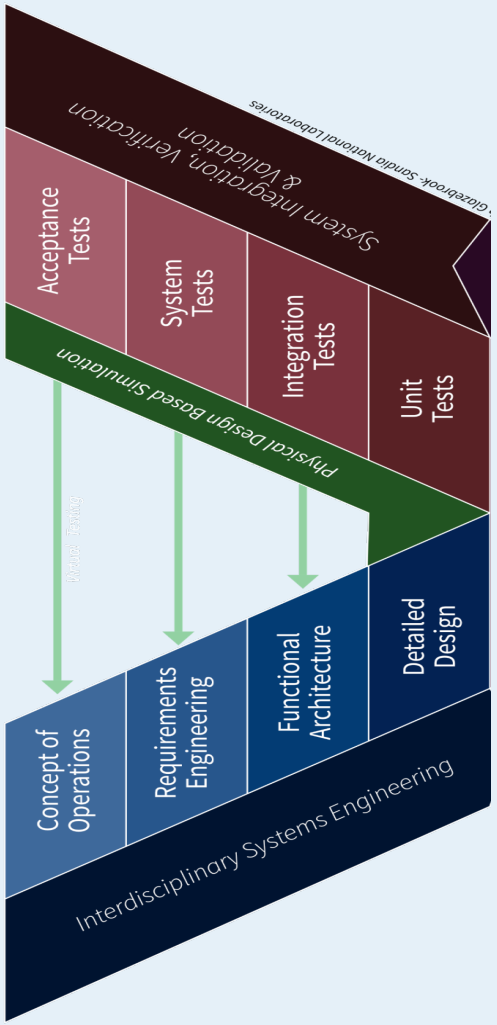

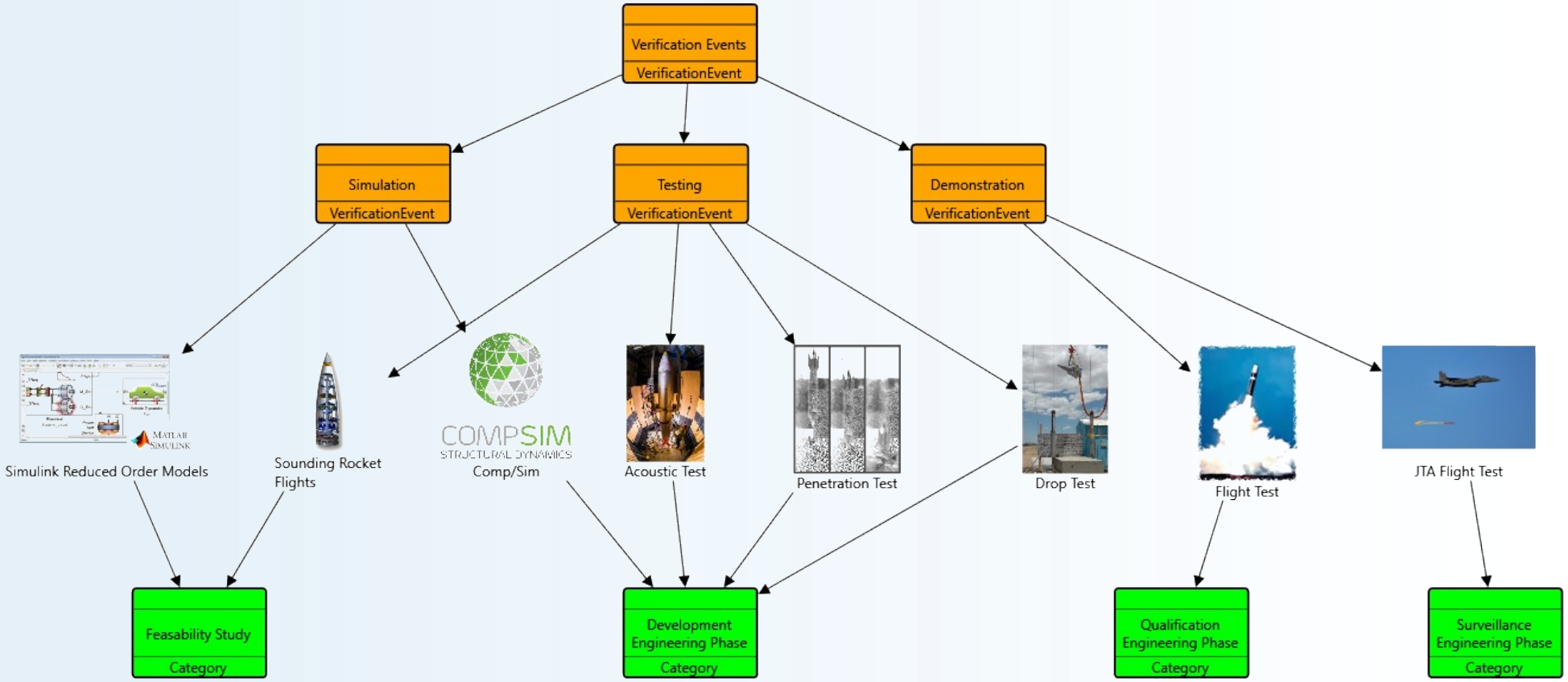

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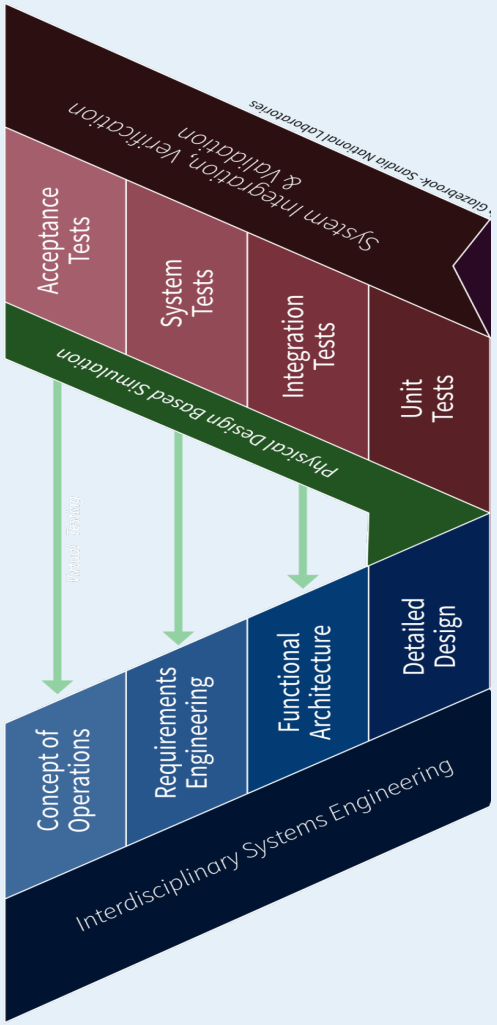

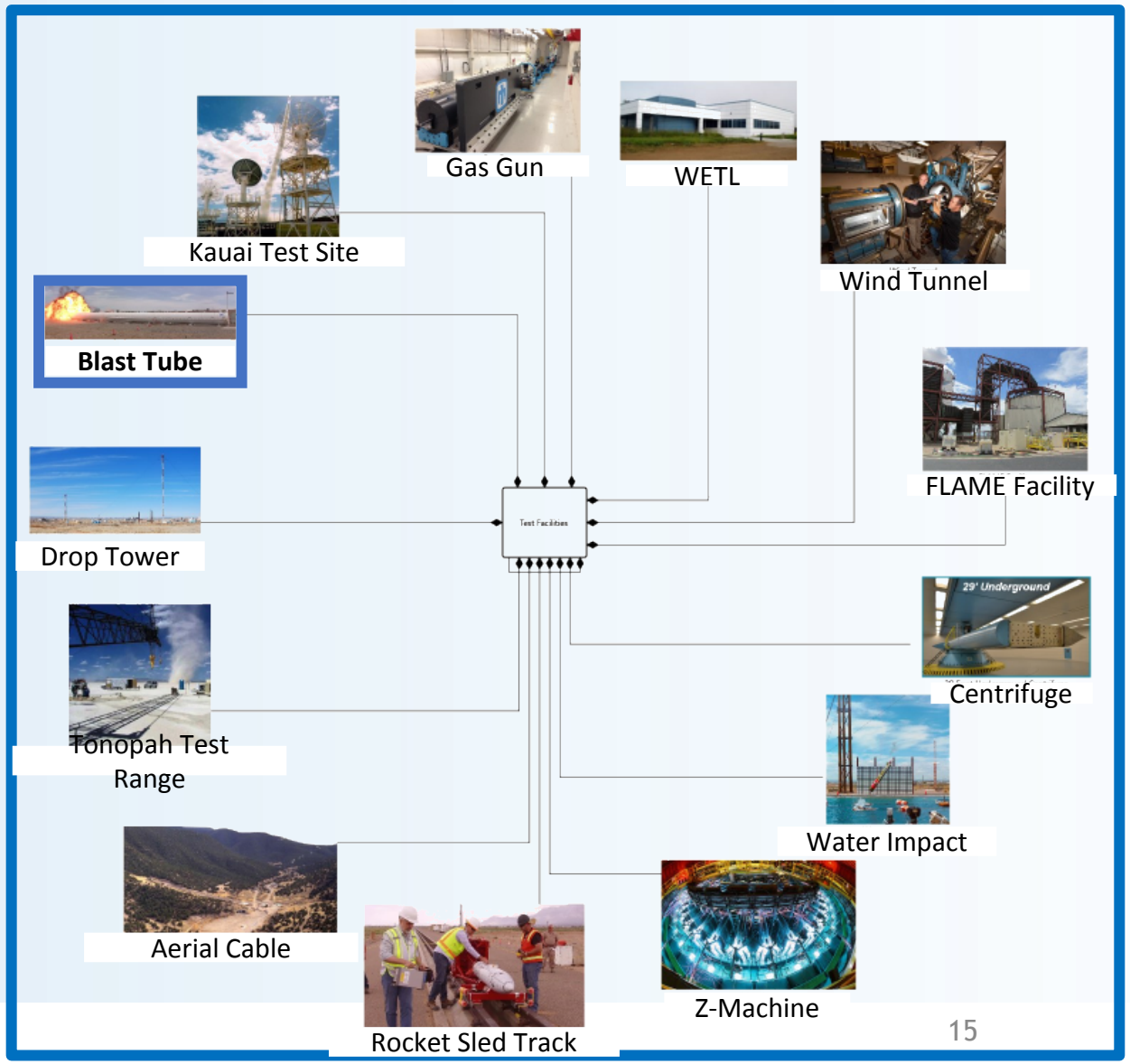

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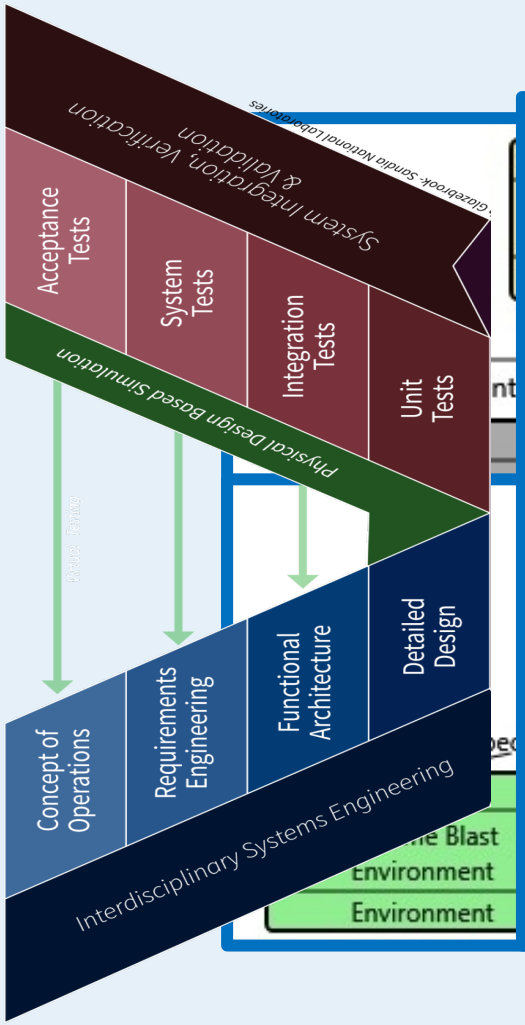
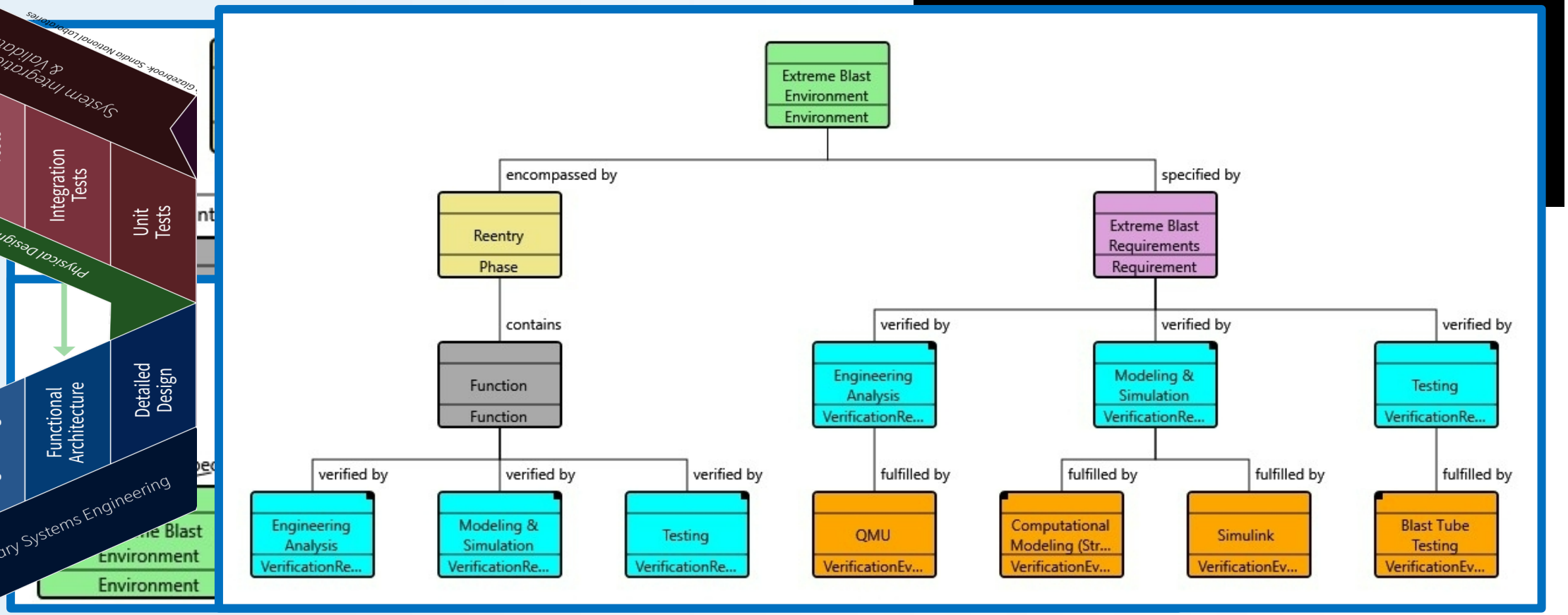




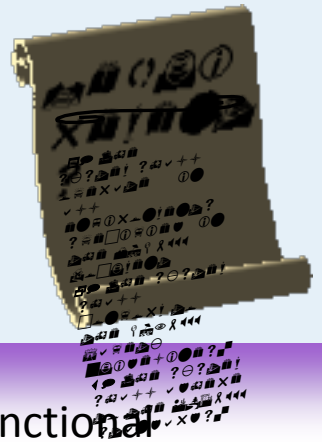
V&V modeling moves the “starting line” to shorten the lifecycle of NW

How Bridging MBSE with Reduced Order Modeling Reduces Development Time

Erik Olson
R&D Electrical Engineering

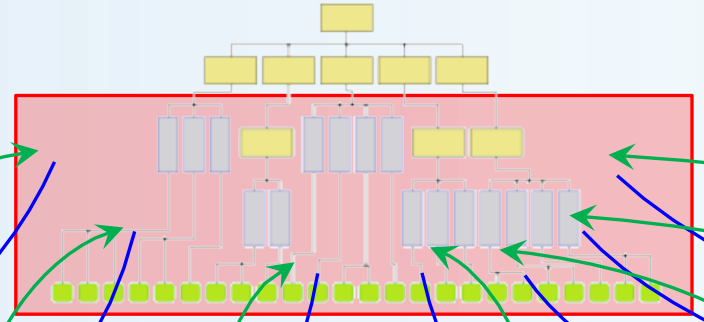
Erik Olson has a background in both Electrical and Mechanical Engineering. He has his PhD in Electrical Engineering from University of Wisconsin. He spent the last ten years working in Sandia's satellite programs, and spent two years as an R&D engineer at Tyco thermal Controls in Menlo Park, California.

The Role of MBSE and Reduced Order Modeling



Functional Models

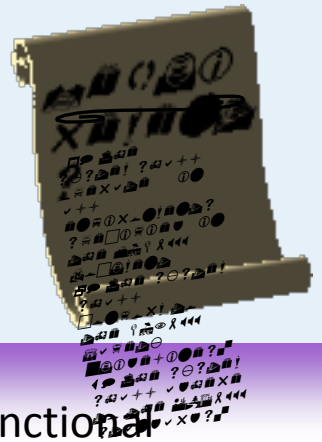
System Architecture



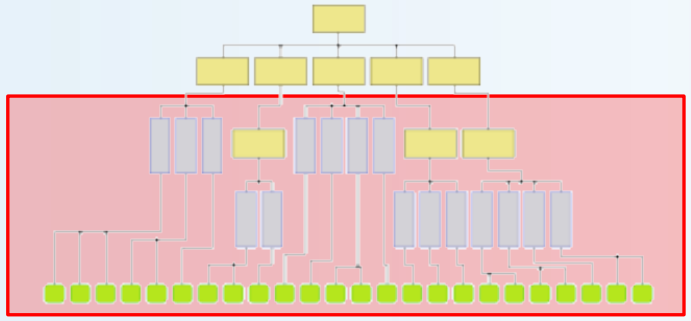
Derived Requirements

Validation

The Role of MBSE and Reduced Order Modeling



System Architecture



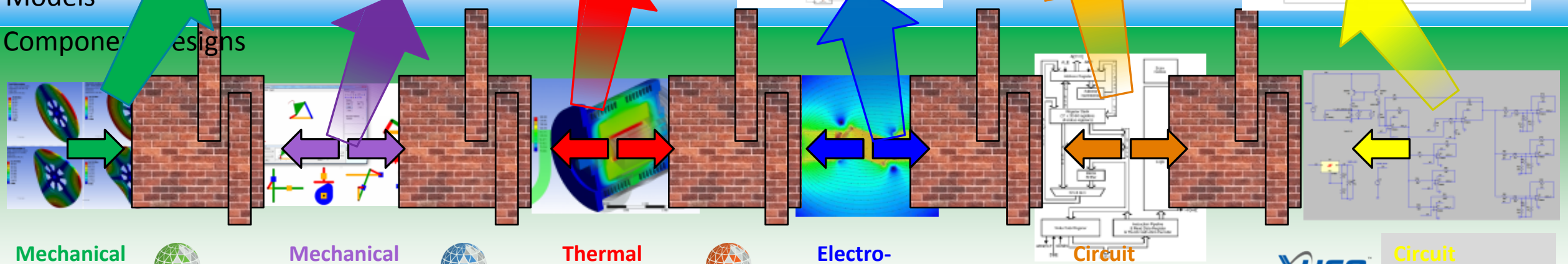
Derived Requirements

Validation

Functional Models

Reduced Order Models

Component Designs



Mechanical Modeling - Vibration

COMPSIM STRUCTURAL DYNAMICS

Mechanical Modeling - Kinematics

COMPSIM SOLID MECHANICS

Thermal Modeling – Conduction

COMPSIM THERMAL FLUIDS

Electro-magnetics

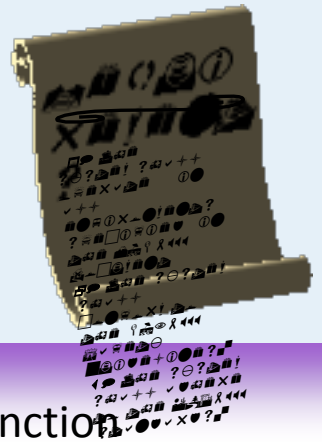
RAMSES

Circuit Modeling – Digital

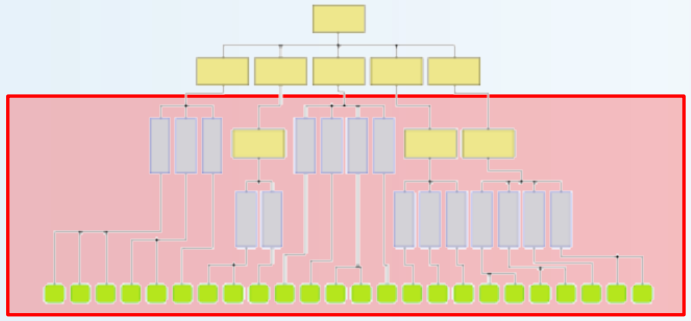
Xyce

Circuit Modeling – Analog / Power

The Role of MBSE and Reduced Order Modeling



System Architecture

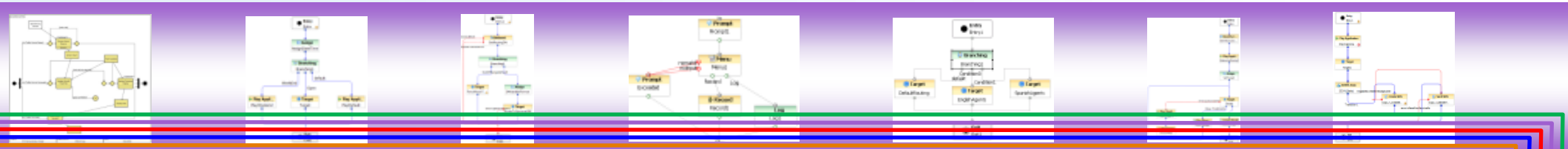


Derived Requirements

Validation

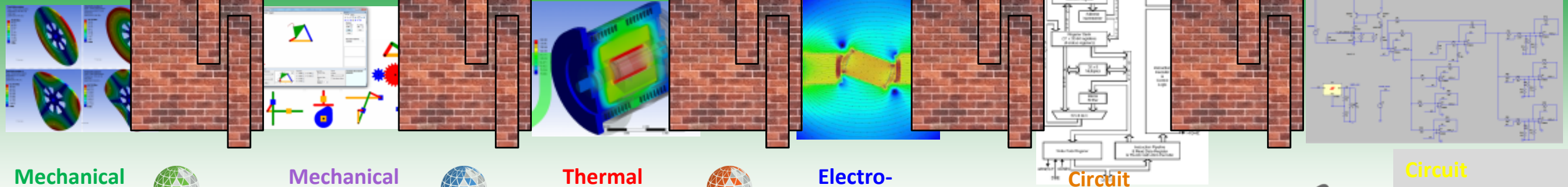
Verification

Function Models



Reduced Order Models

Component Designs



Mechanical Modeling - Vibration

COMPSIM STRUCTURAL DYNAMICS

Mechanical Modeling - Kinematics

COMPSIM SOLID MECHANICS

Thermal Modeling – Conduction

COMPSIM THERMAL FLUIDS

Electro-magnetics

RAMSES

Circuit Modeling – Digital

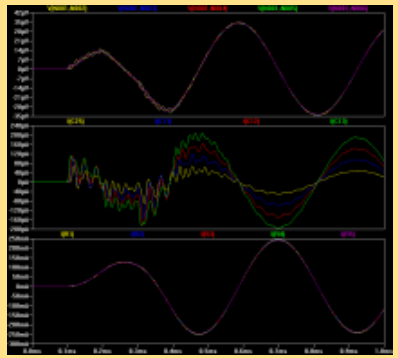
Xyce

Circuit Modeling – Analog / Power

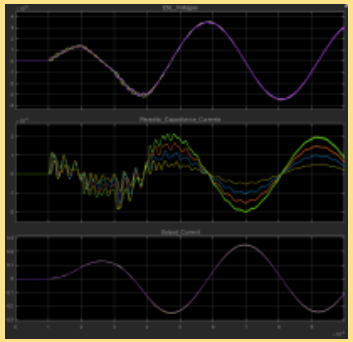
Equivalent Simulink Models

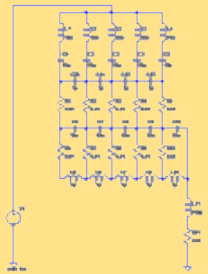
Passive Coupled Networks

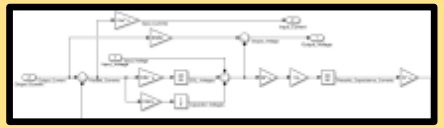
LTSpice



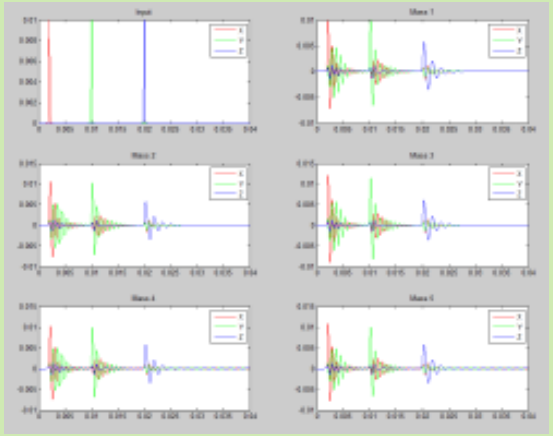
SIMULINK

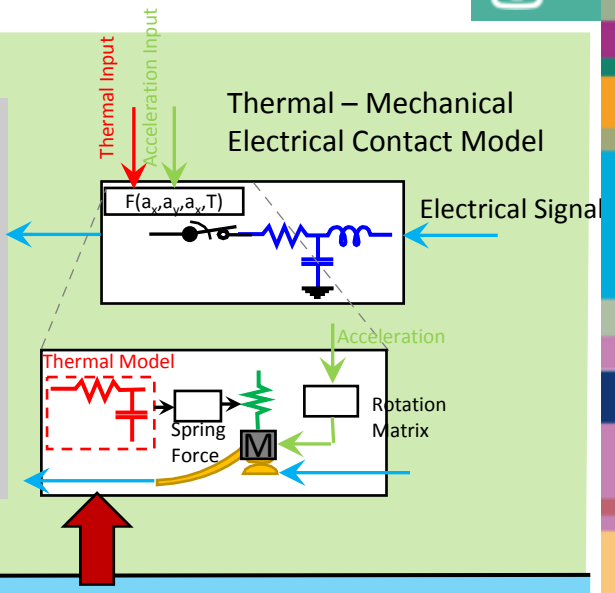






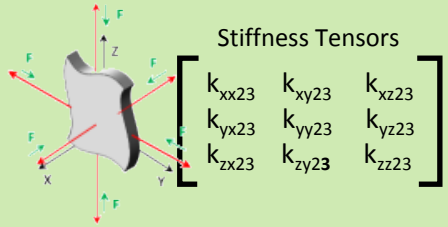
Mechanical Vibration / Electrical



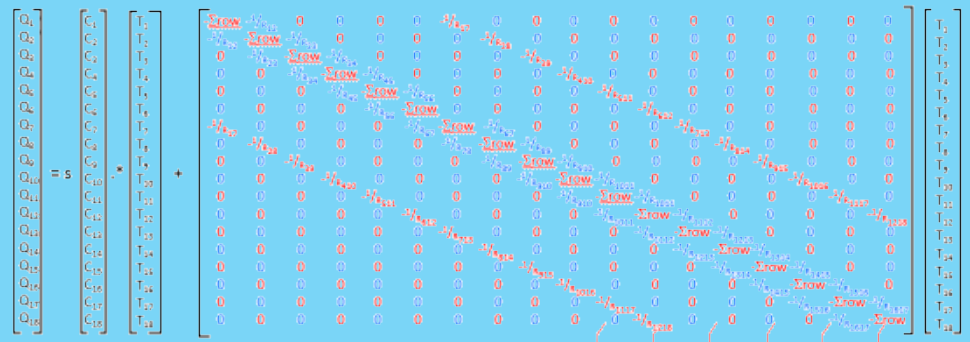


Electrical Contact Chatter

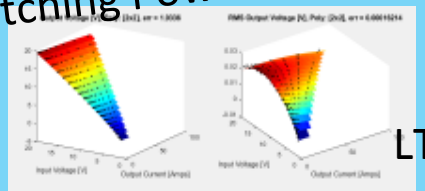
Mechanical Vibe



Thermal Conduction Models

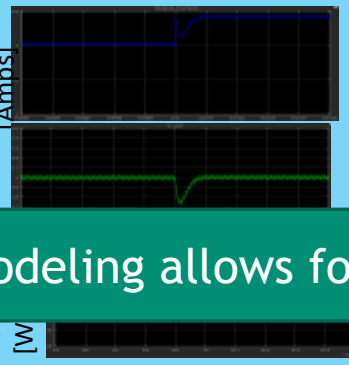


Switching Power Converter Models

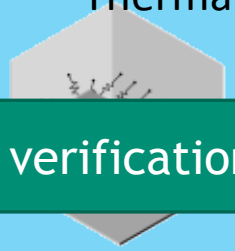


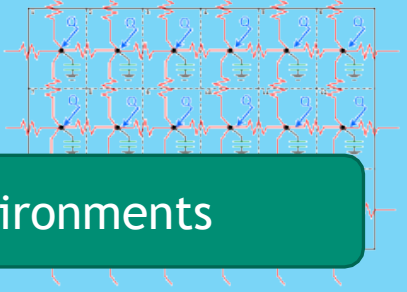
LTSpice

SIMULINK



Thermal Radiation Models





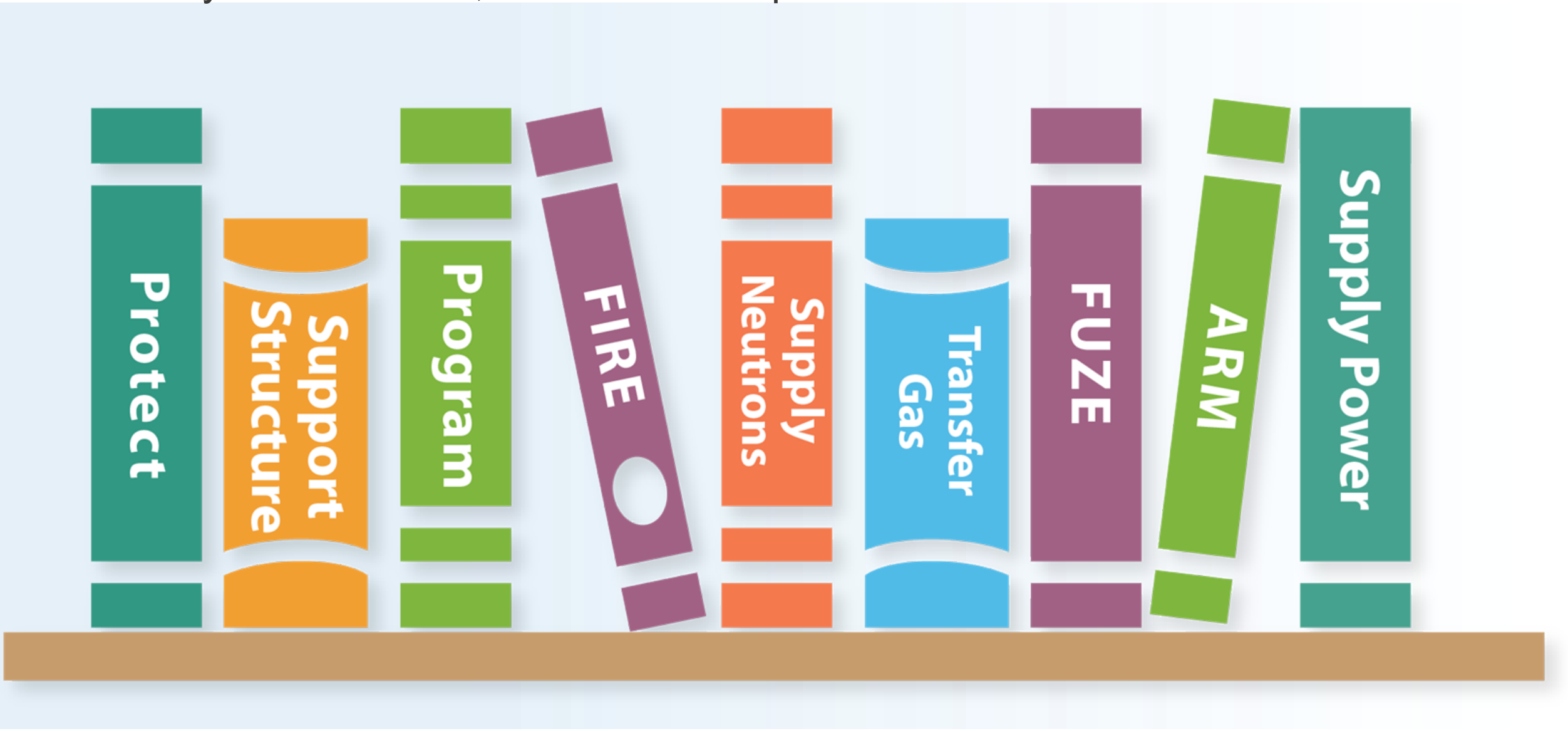
Reduced Order Modeling allows for virtual cycle verification with combined environments

How Data Strategy For The Digital Twin Reduces NW Development Time

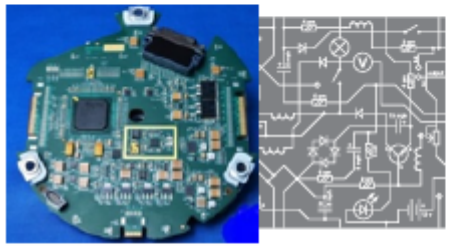
Ryan Coleman
R&D Computer Scientist

Ryan has experience in abnormal environments and detonator modeling, and many of the advanced simulation and computing analyses for nuclear weapons qualification. Immediately prior to joining Sandia, Ryan was an academic postdoc in Pharmaceutical Chemistry at University of California San Francisco, where he built and used software systems for drug discovery. Ryan has degrees in Computer Science, Philosophy, and his PhD in Computational Biology.

Library of Functions; Books of Components

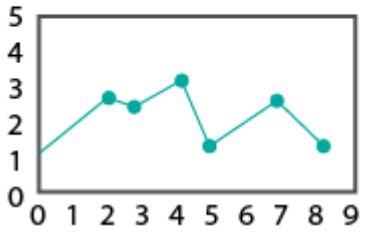


Library of Functions; Books of Components



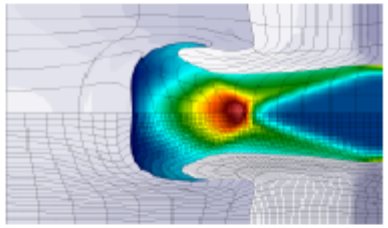
Mk2017 Design

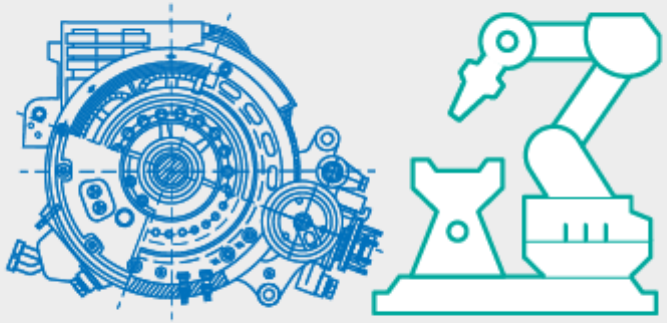
Development Data



Environment & Margins

Simulation Models





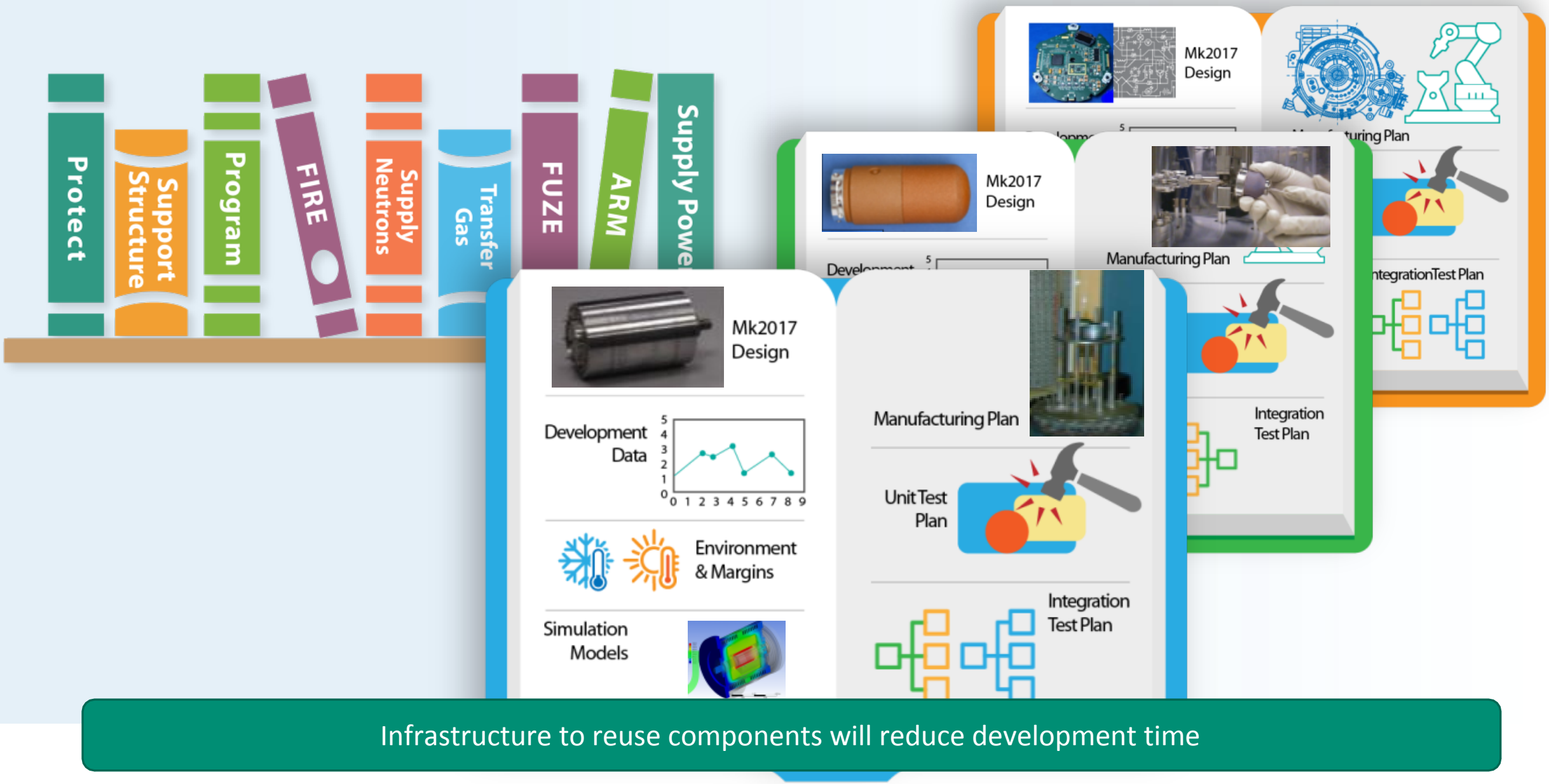
Manufacturing Plan

Unit Test Plan

IntegrationTest Plan

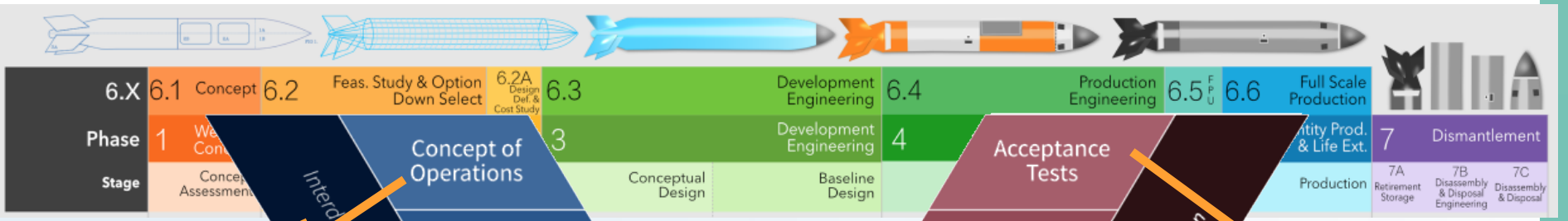
A Digital Twin for Components allows them to be reused to shorten development time

Library of Functions; Books of Components



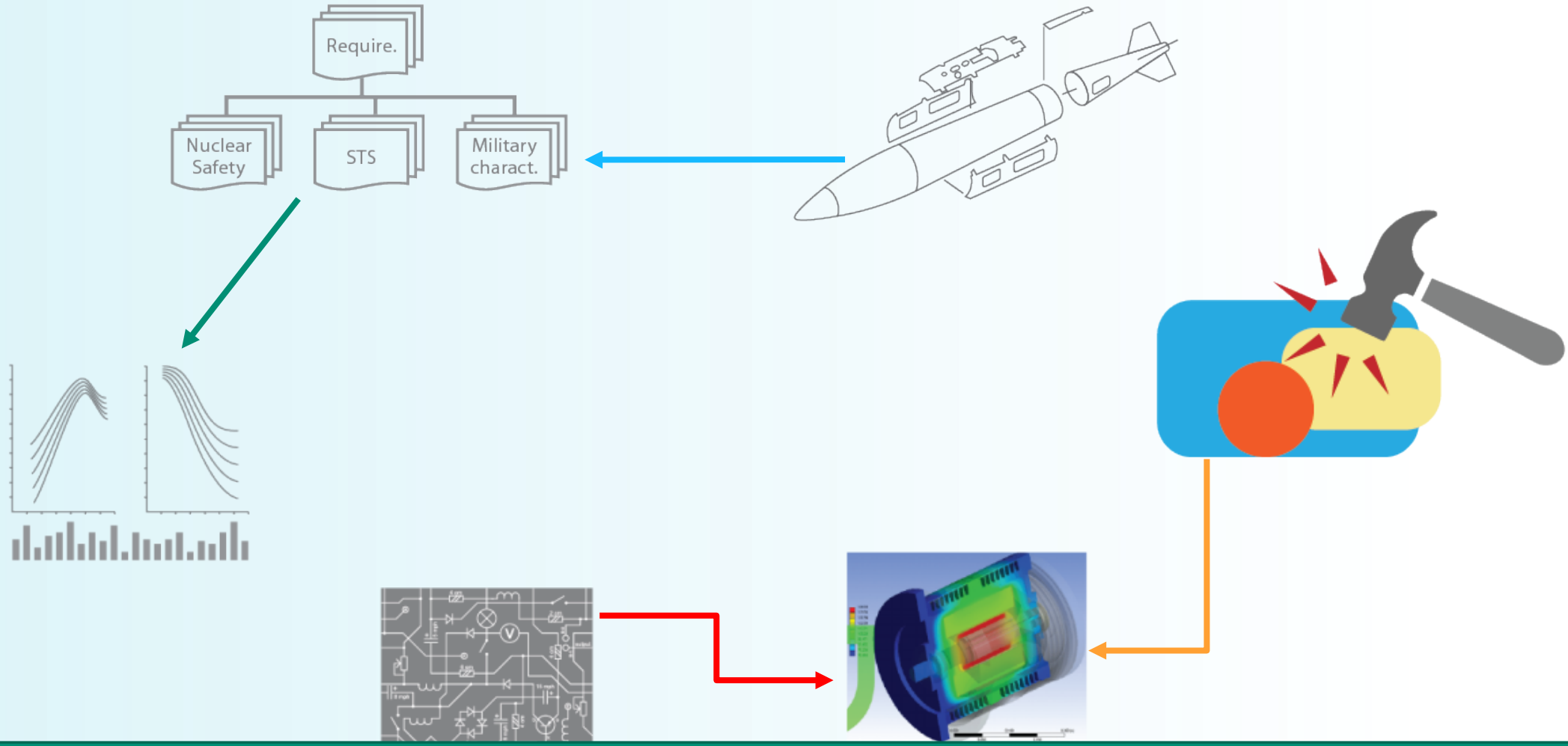
Infrastructure to reuse components will reduce development time

Time



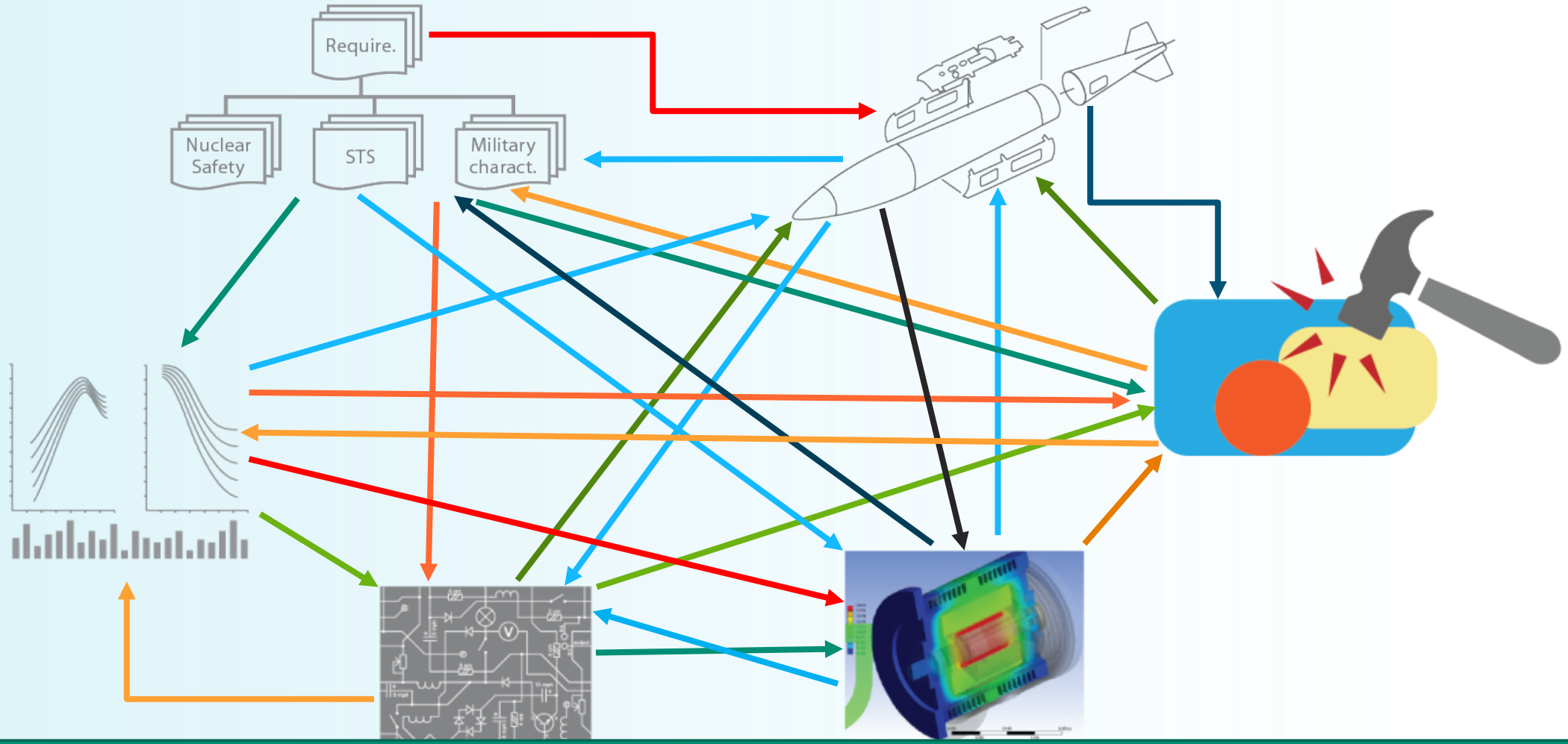
Digital Twin of Each Weapon System will reduce development time

Architecting the Connections Between Diverse and Disparate Sources



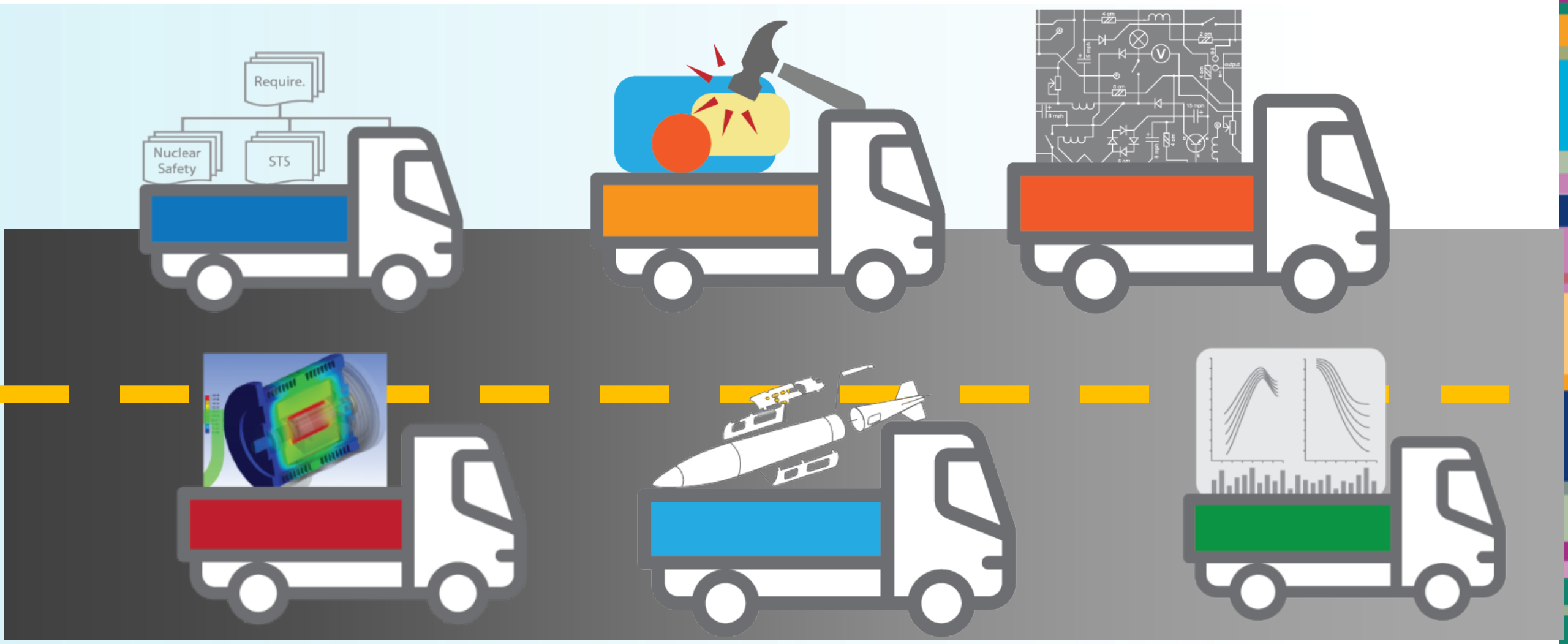
Connecting Data Sources will be Necessary For Success

Architecting the Connections Between Diverse and Disparate Sources



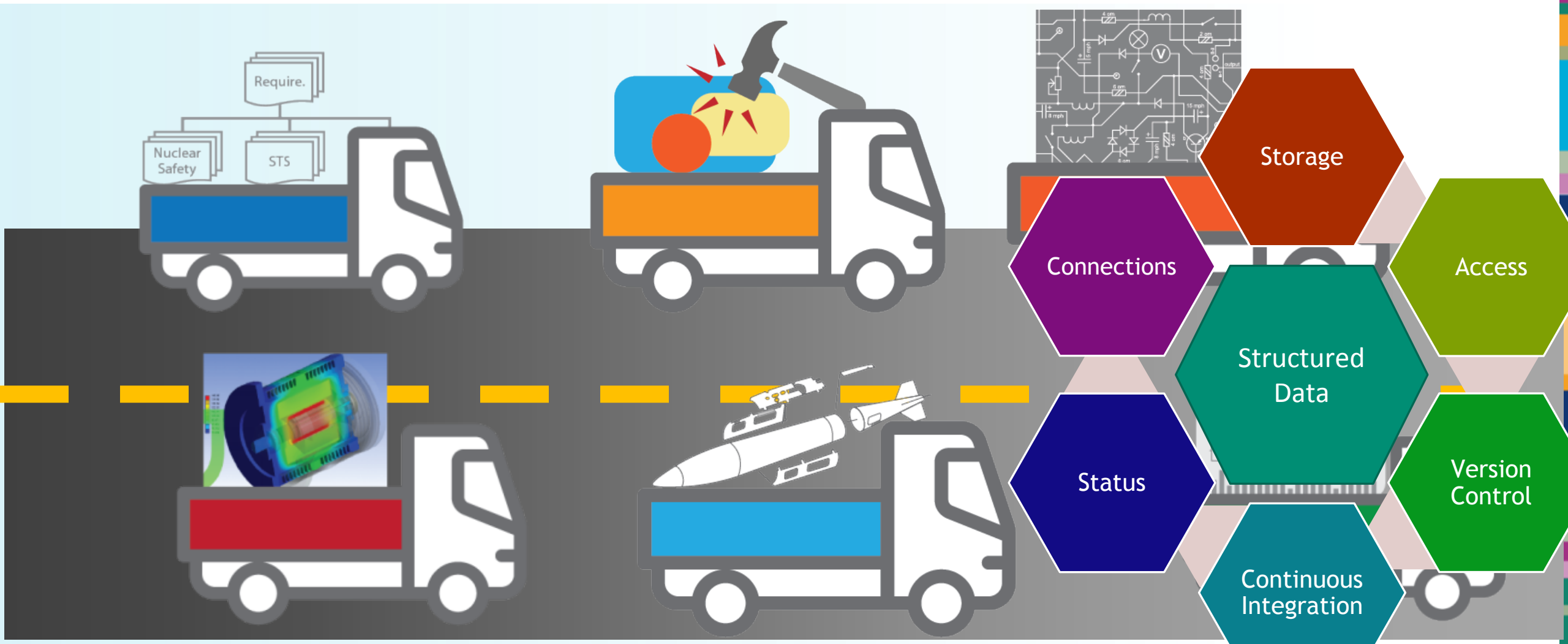
But A Quadratic Number of Data Translations Will Be Unmanageable

Merging Complex Data Sources



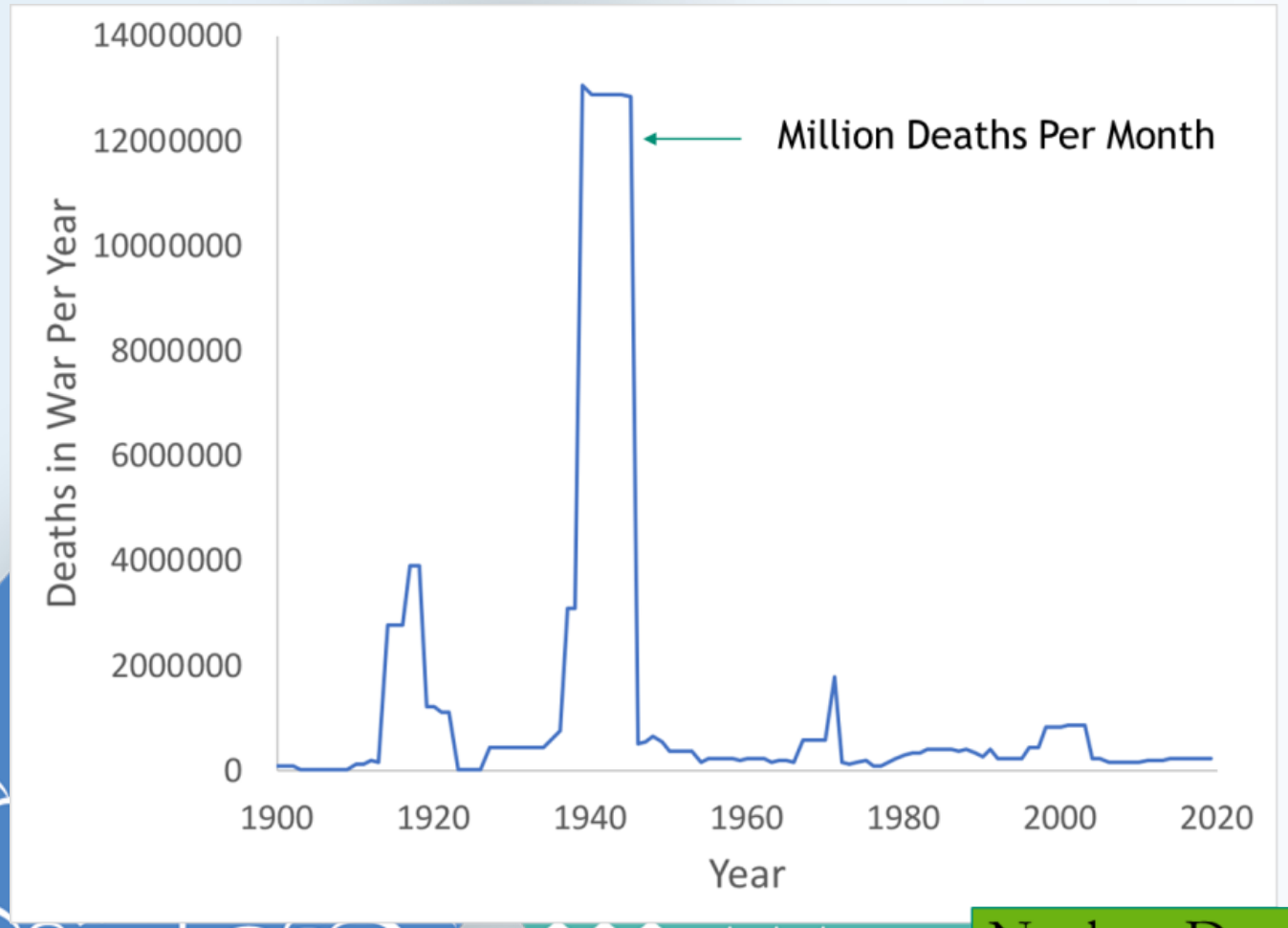
Build a Single Data Layer (Road) to Move Data, along with one Adapter (Truck) per Data Source

Merging Complex Data Sources



Allows Data Storage, Warehousing, Version Control, Access Control to be built in a Single Place

Nuclear Deterrence



Nuclear Deterrence Works

Respond to Threats, Sustained Deterrence

Tip-to-Tail System Modeling Using Reduced Order Modeling

PRESENTED BY

Erik Olson, 2496

December 10, 2018

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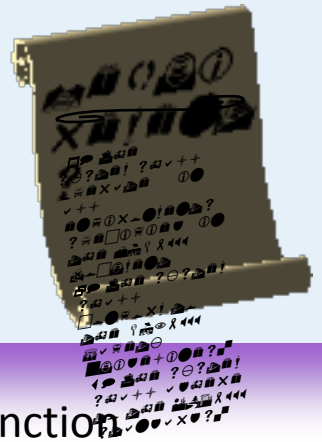
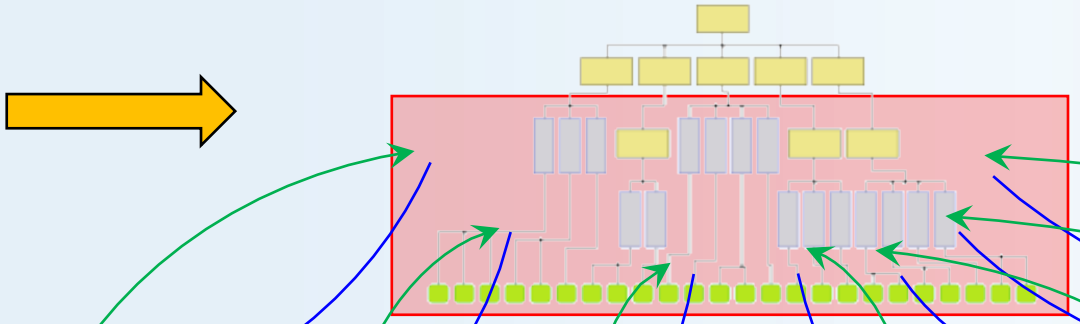
The Role of MBSE and Reduced Order Modeling



Function Models

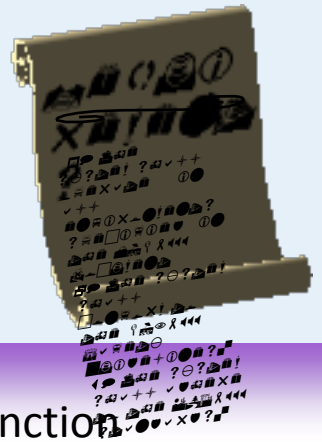
System Architecture



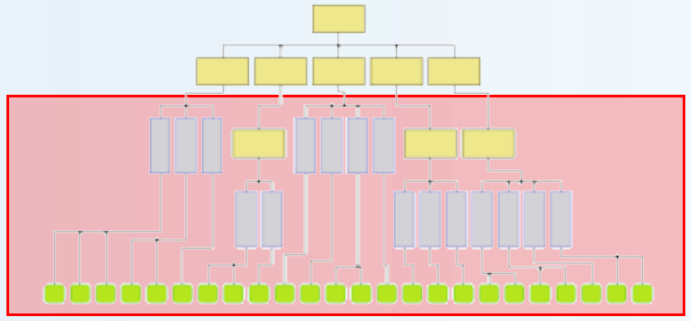
Derived Requirements

Validation

The Role of MBSE and Reduced Order Modeling



System Architecture



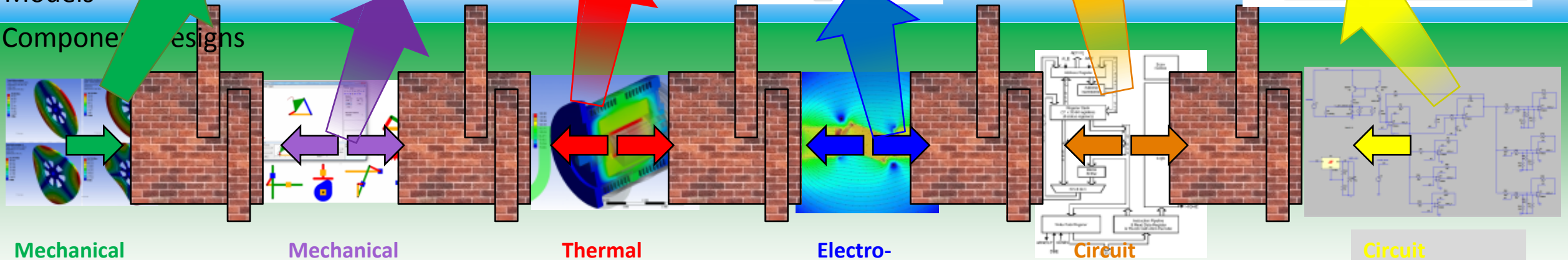
Derived Requirements

Validation

Function Models

Reduced Order Models

Compone esigns



Mechanical Modeling - Vibration

Mechanical Modeling - Kinematics

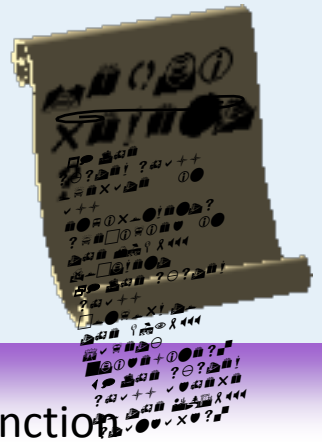
Thermal Modeling – Conduction

Electro-magnetics

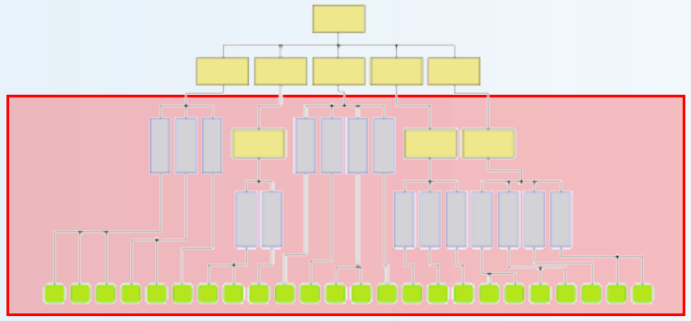
Circuit Modeling – Digital

Circuit Modeling – Analog / Power

The Role of MBSE and Reduced Order Modeling

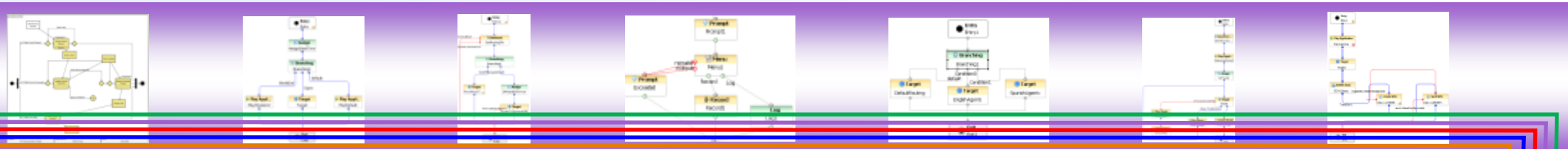


System Architecture



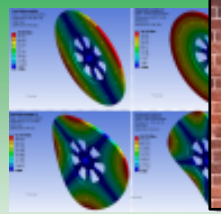
Derived Requirements

Function Models

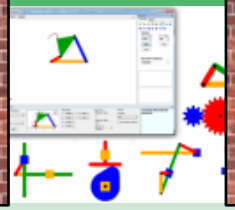


Reduced Order Models

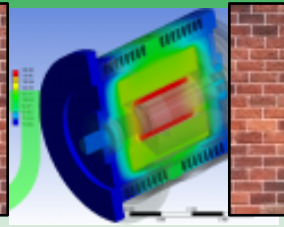
Component Designs



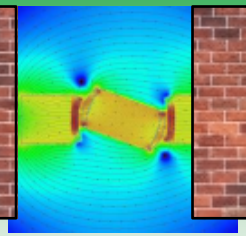
Mechanical Modeling - Vibration



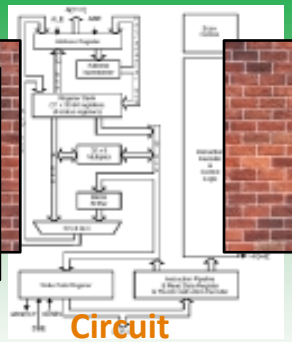
Mechanical Modeling - Kinematics



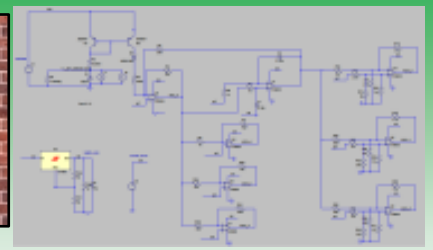
Thermal Modeling – Conduction



Electro-magnetics



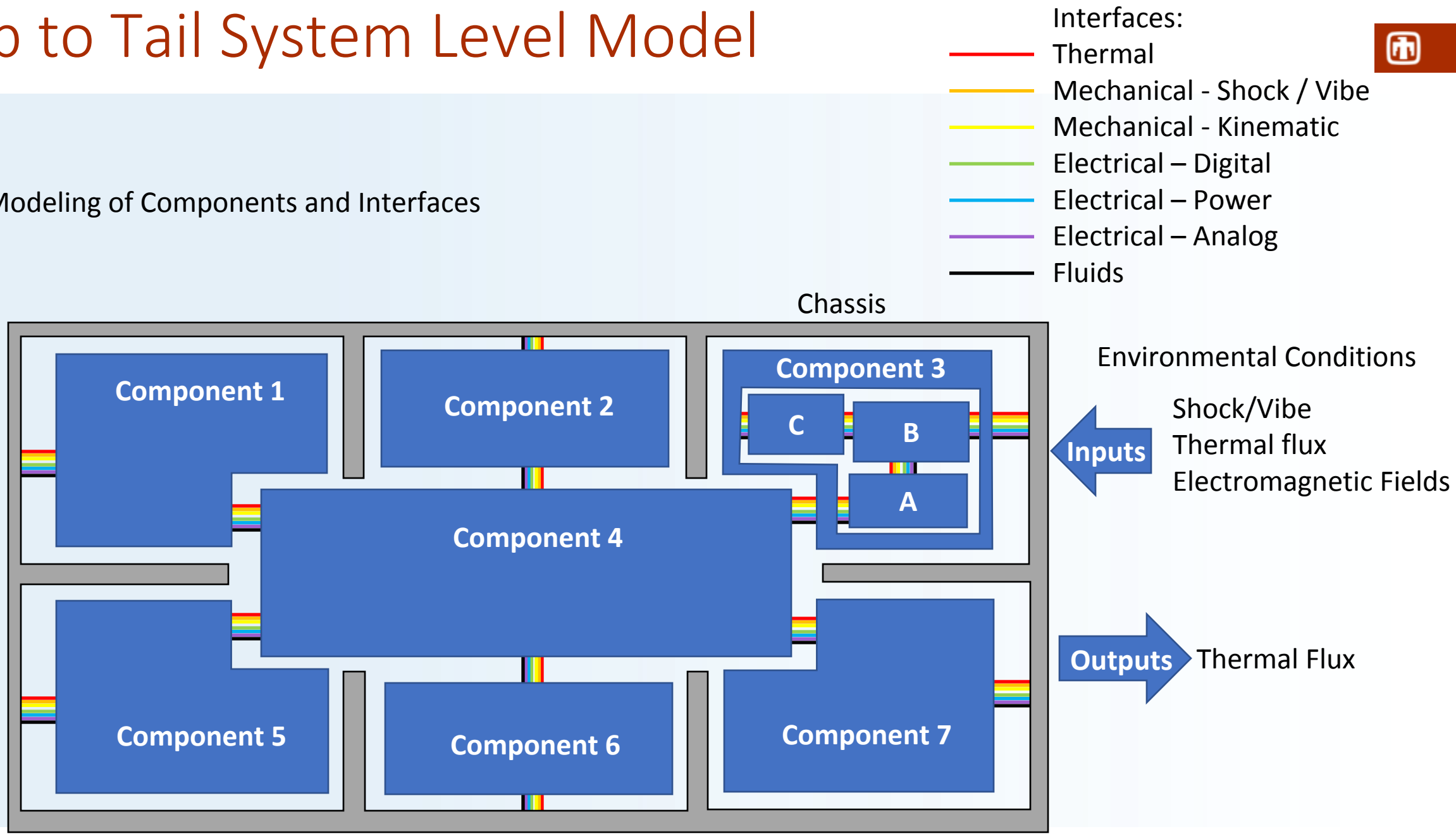
Circuit Modeling – Digital



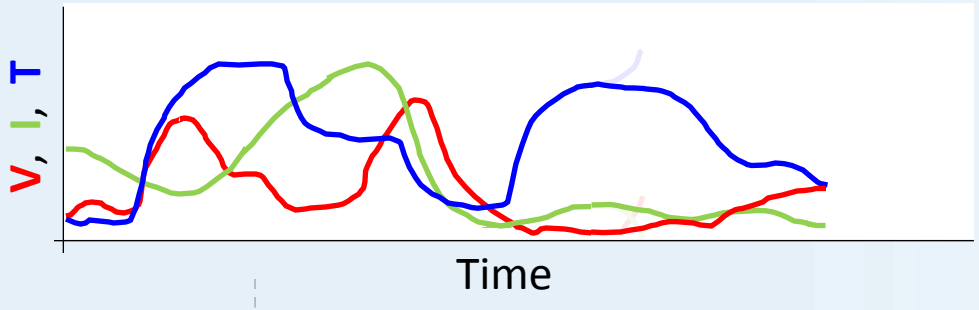
Circuit Modeling – Analog / Power

Tip to Tail System Level Model

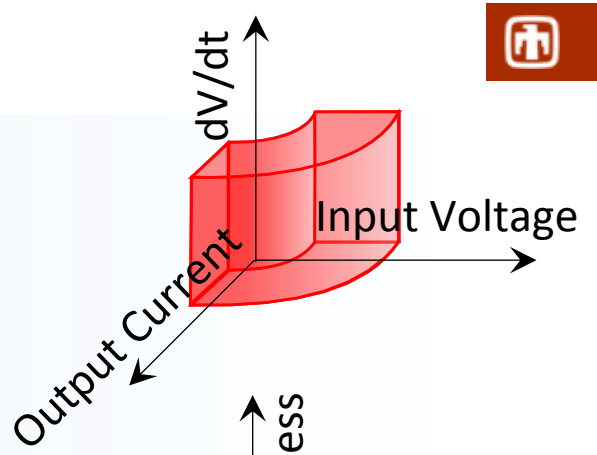
Modeling of Components and Interfaces

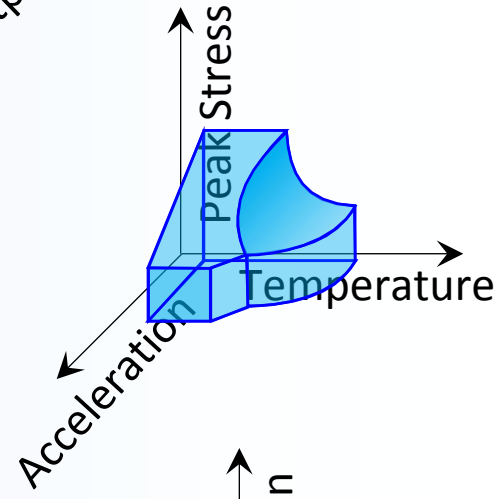


Physics Variable Trajectories



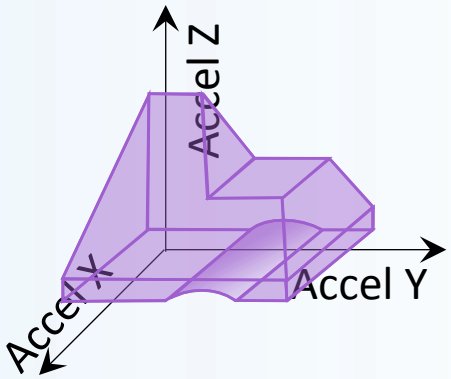
Region of high accuracy, high confidence
Behavioral
Possibly Linear
"Ideal" performance
Verified against physics design model
(Finite Element, PSPICE)

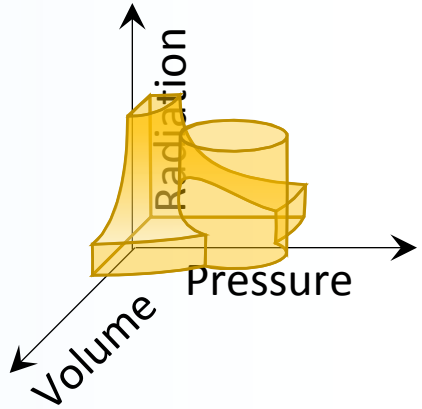


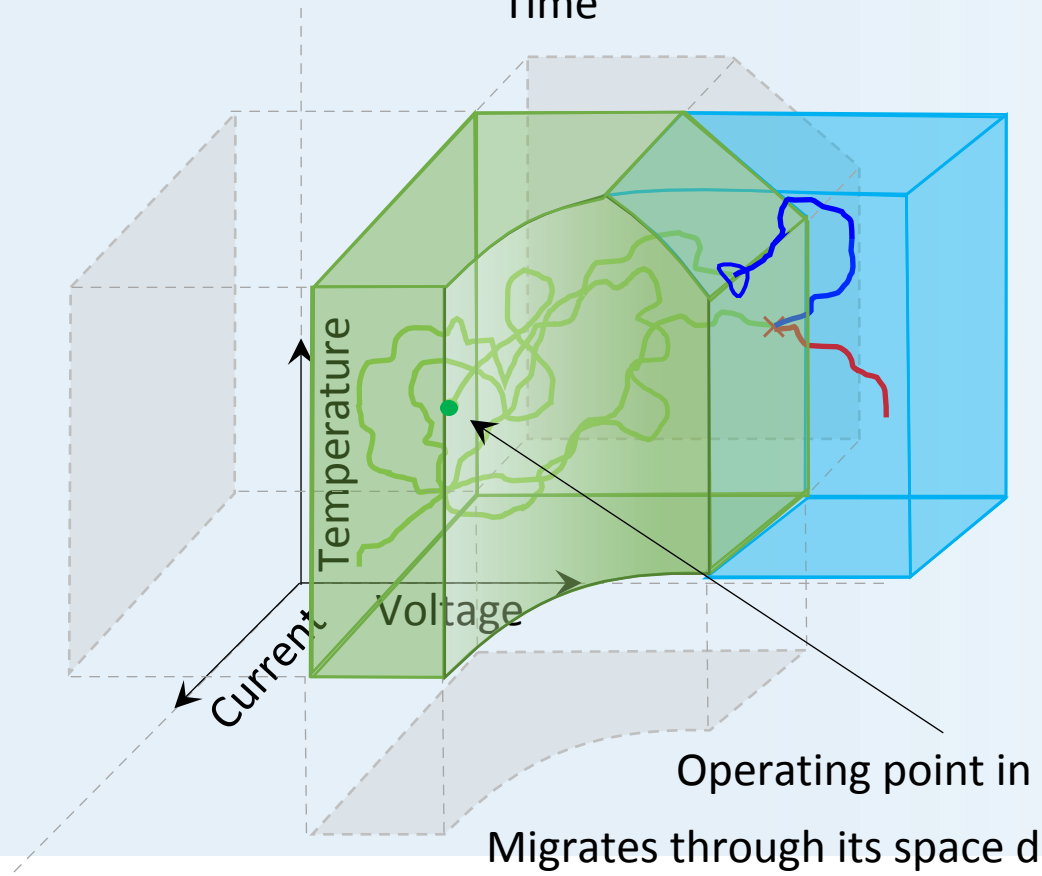


If external conditions force the modeled component beyond its limits of accuracy,

A piece-wise extended model can be made to extend the accuracy of the component's model, if necessary.



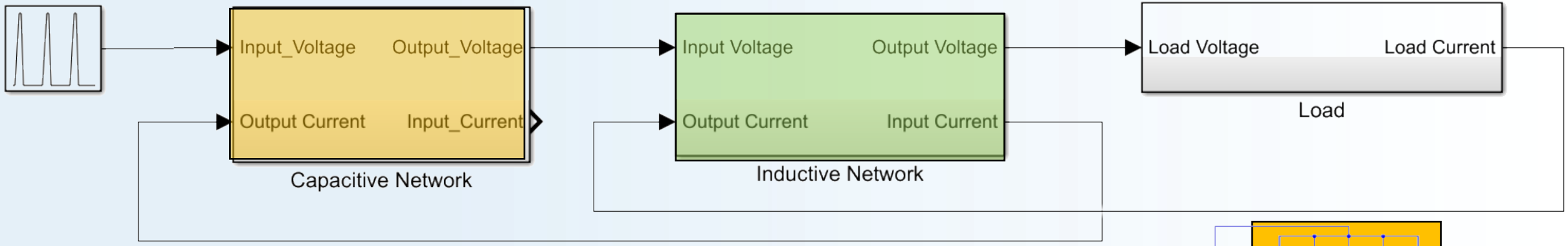


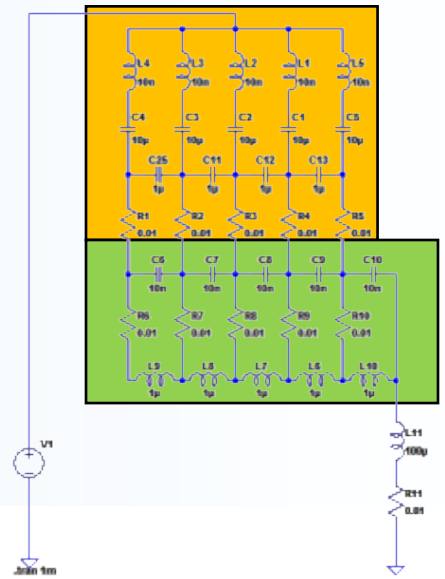


Operating point in simulation space

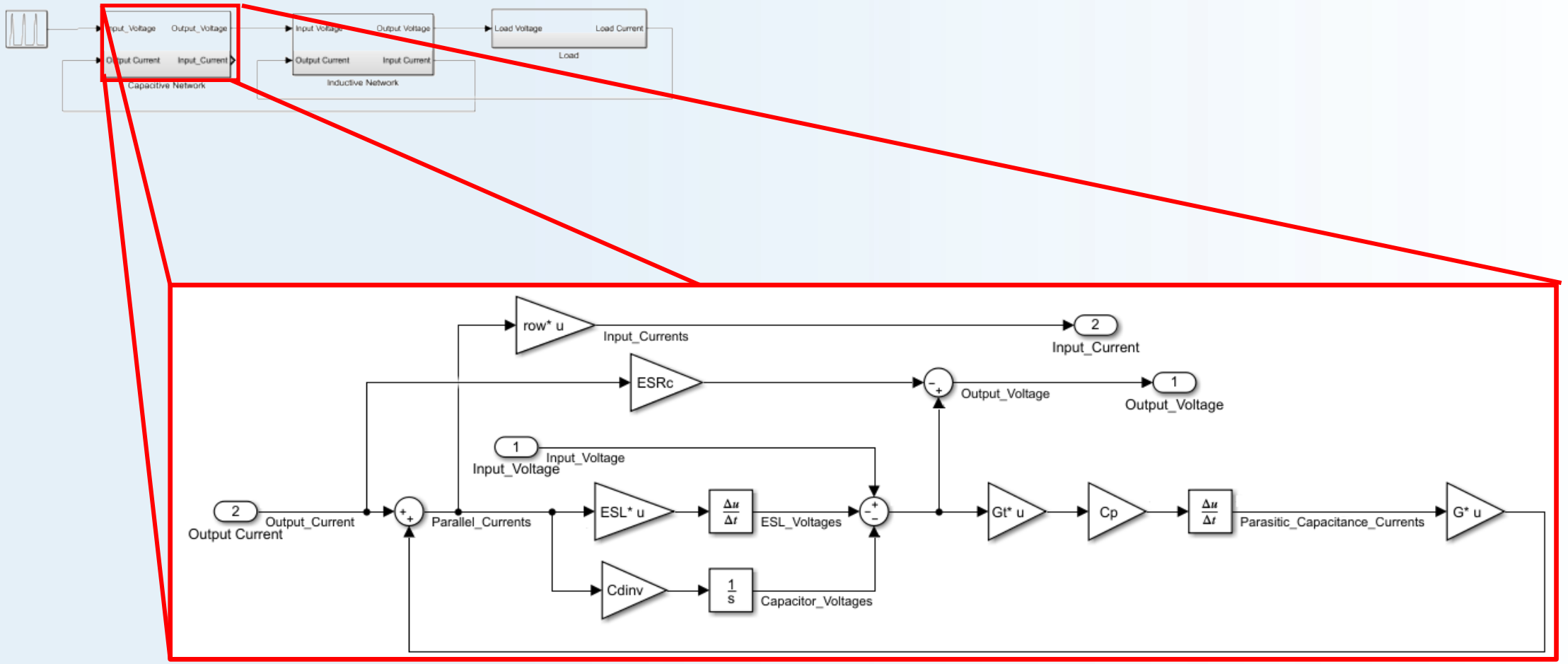
Migrates through its space during a simulation

Connecting Passive Electrical Components



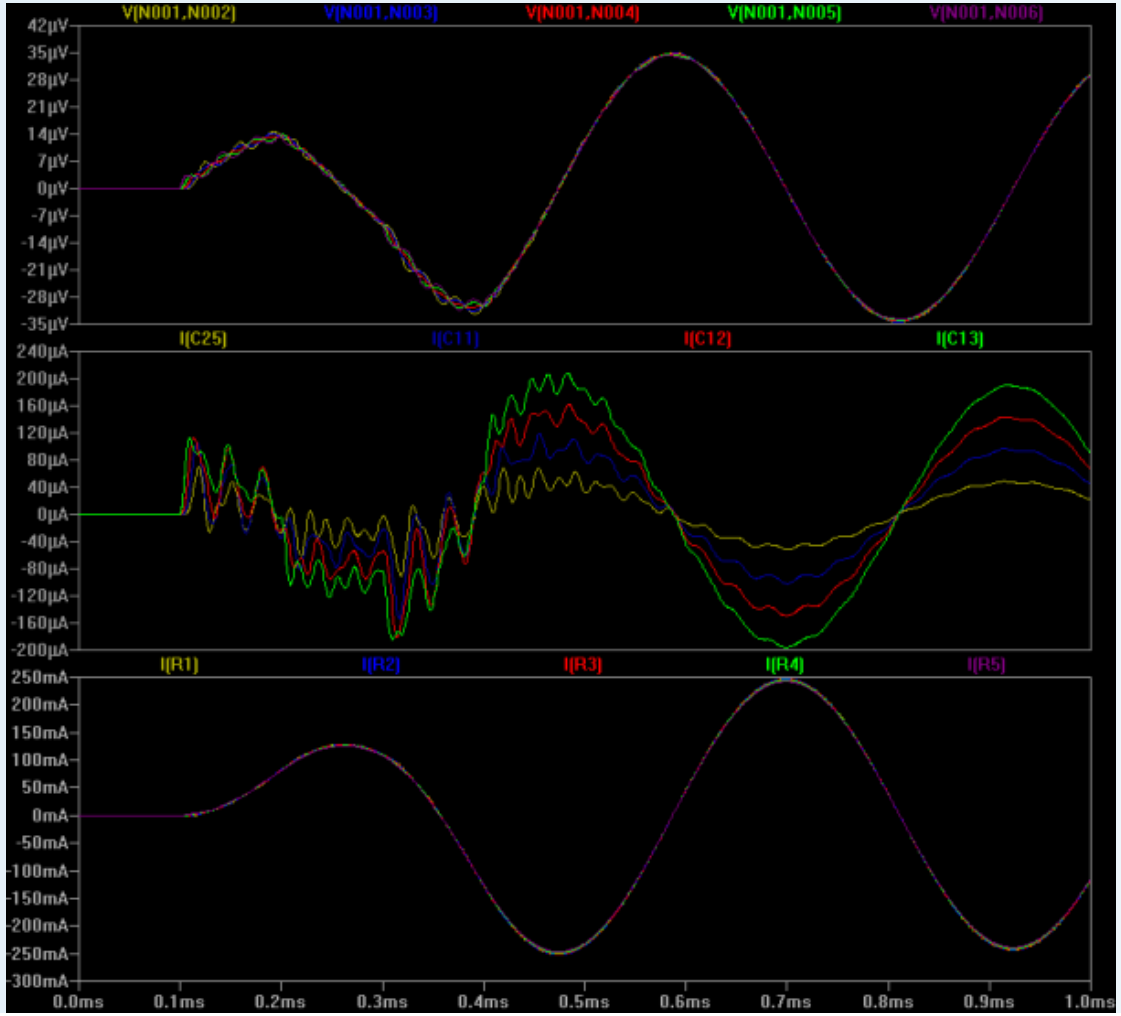


Electrical Modeling

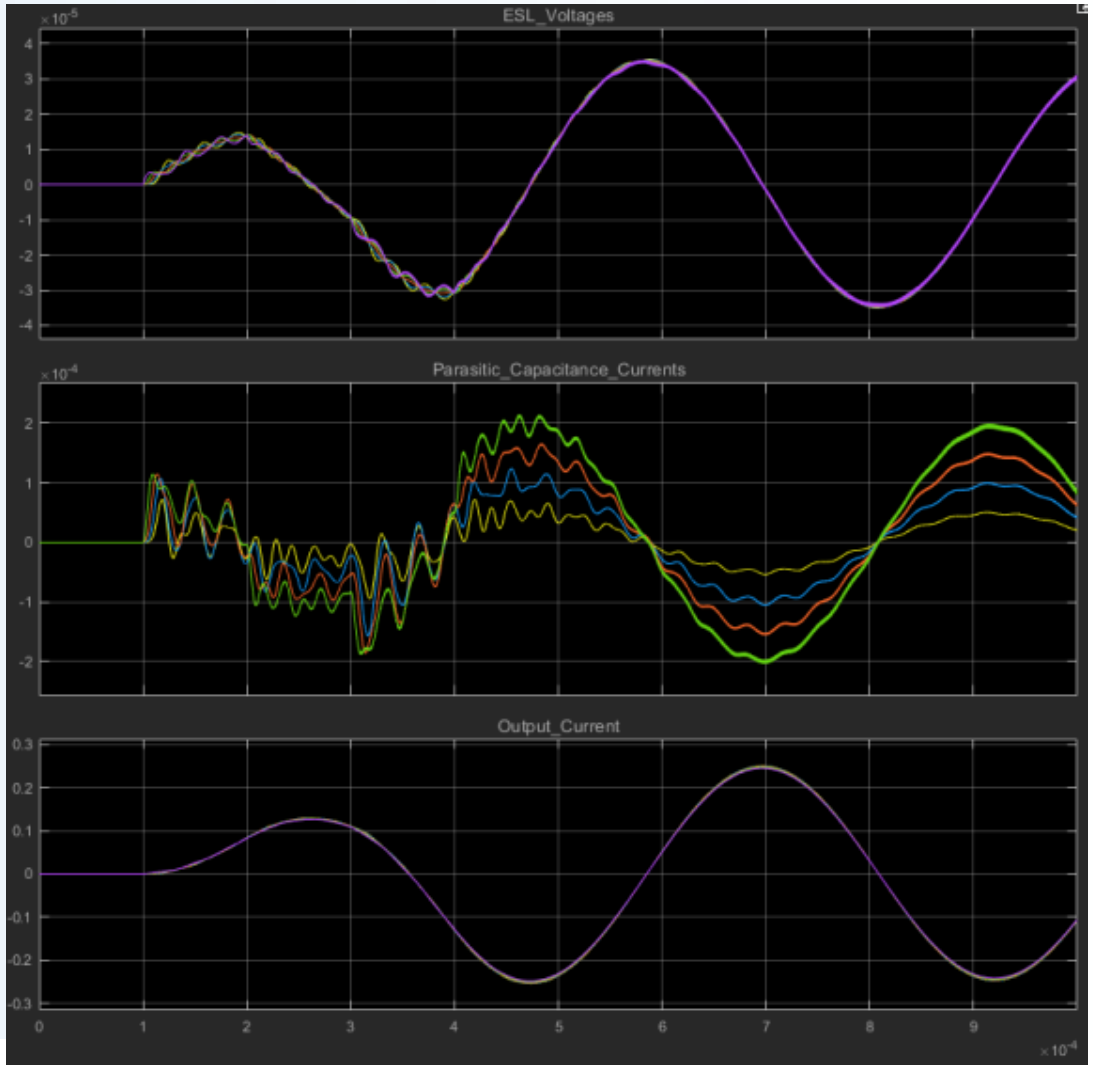


Electrical Modeling

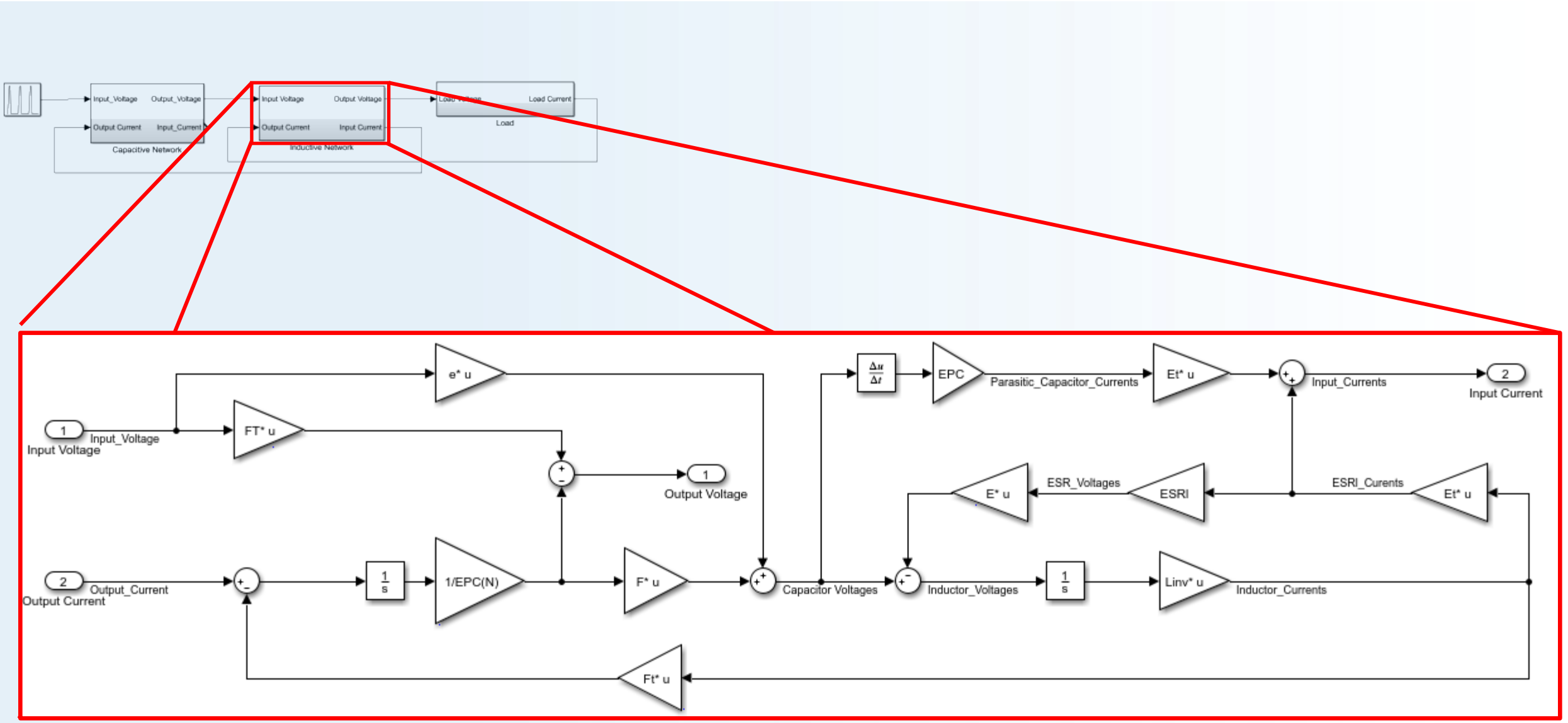
LTSpice



SIMULINK

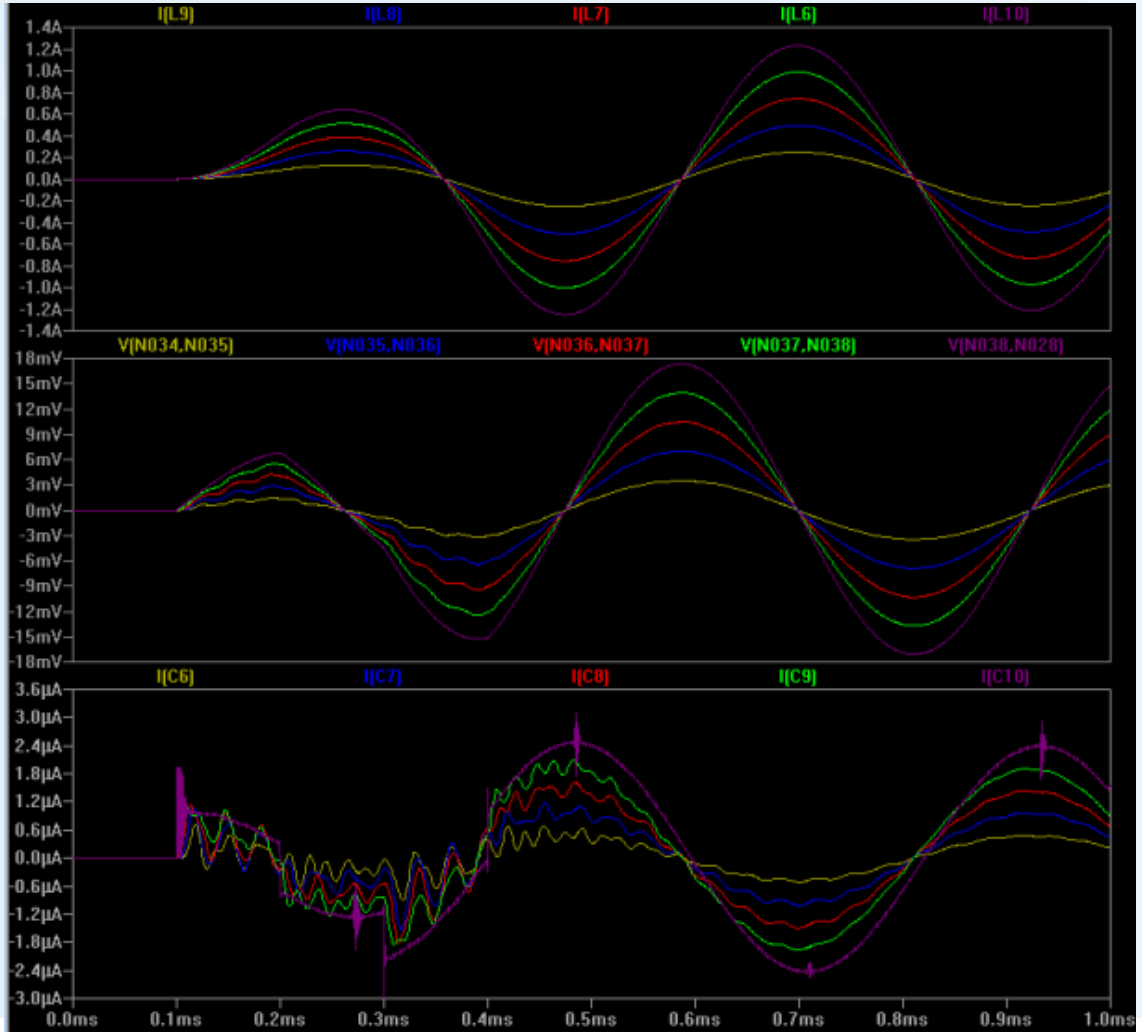


Electrical Modeling

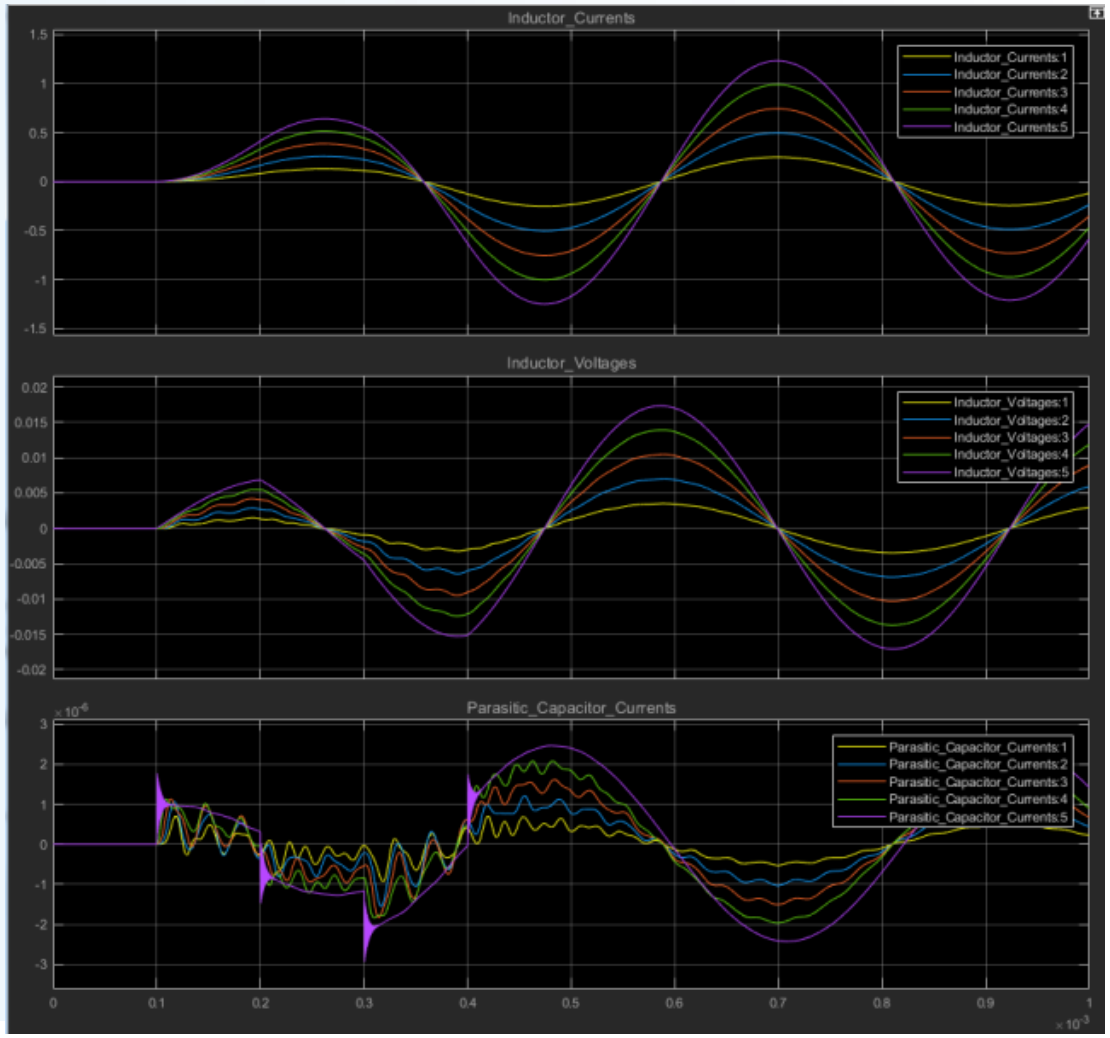


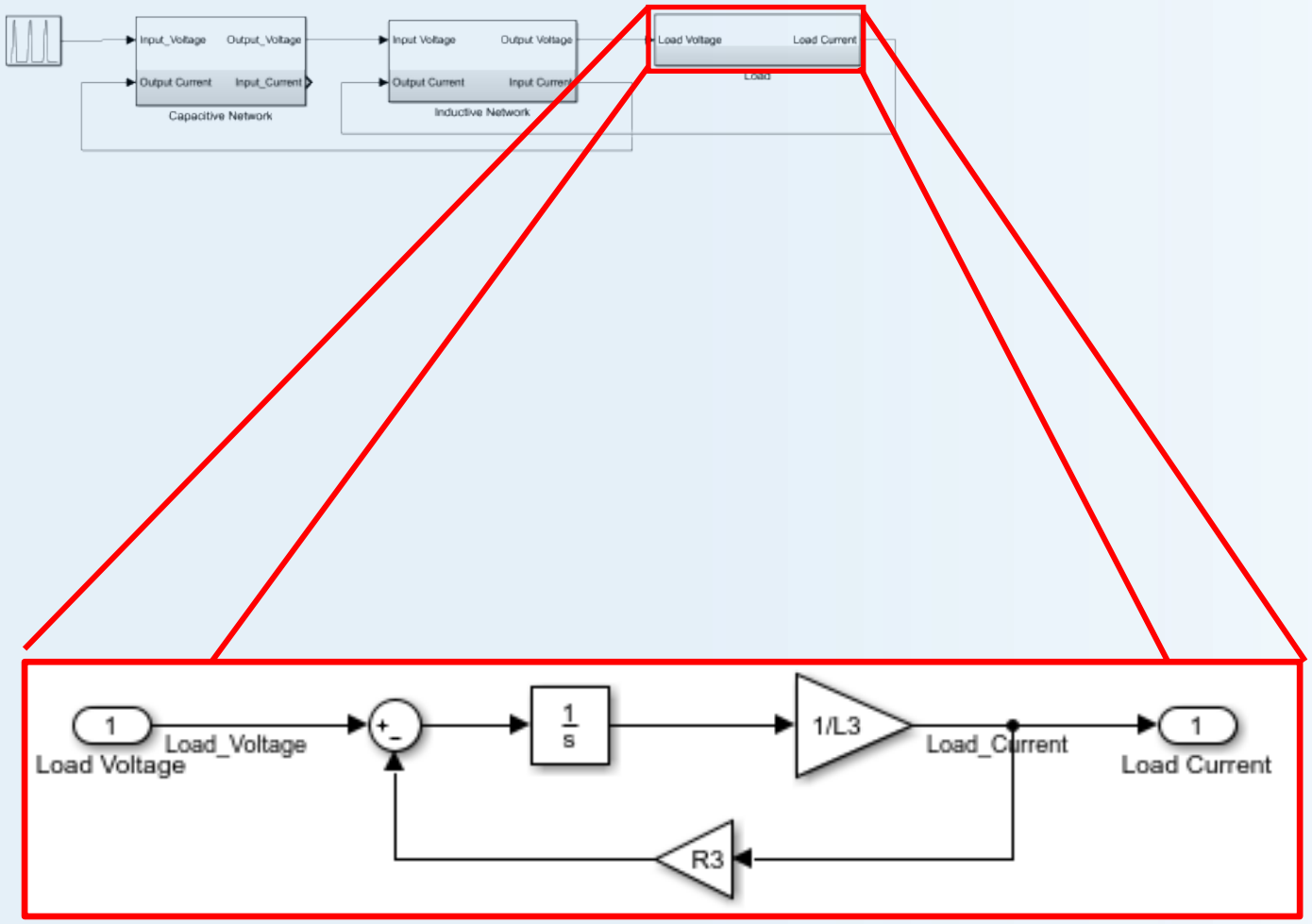
Electrical Modeling

LTSpice

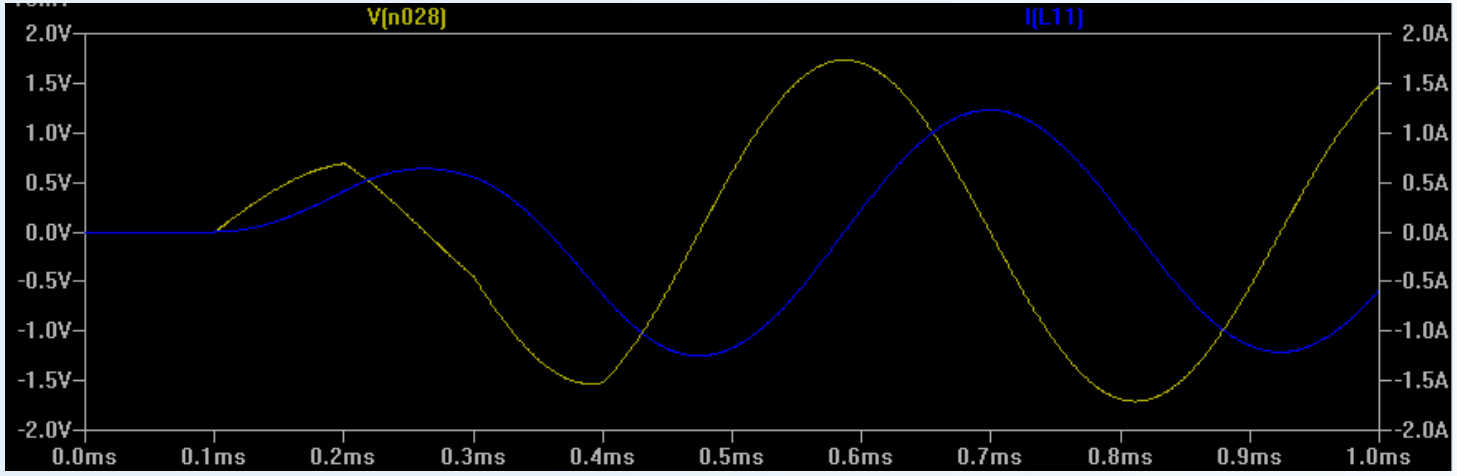


SIMULINK




Input_Voltage
Output_Voltage
Output Current
Input_Current
Capacitive Network
Input Voltage
Output Voltage
Output Current
Input Current
Inductive Network
Load Voltage
Load Current
Load
1
Load_Voltage
Load Voltage
1
s
1/L3
Load_Current
1
Load Current
R3

Electrical Modeling



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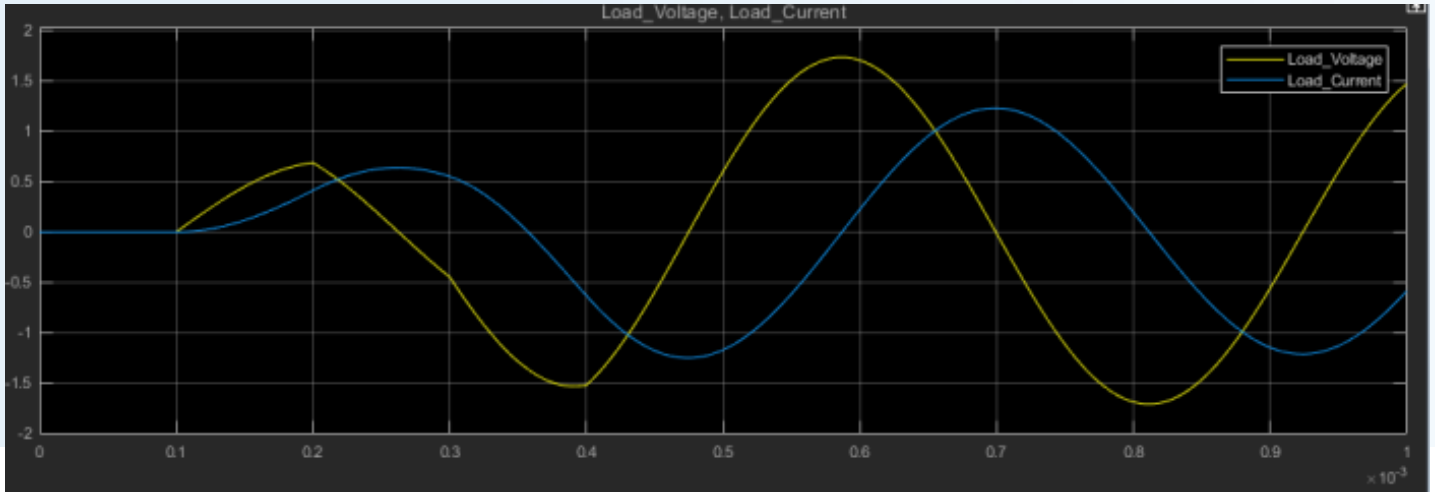
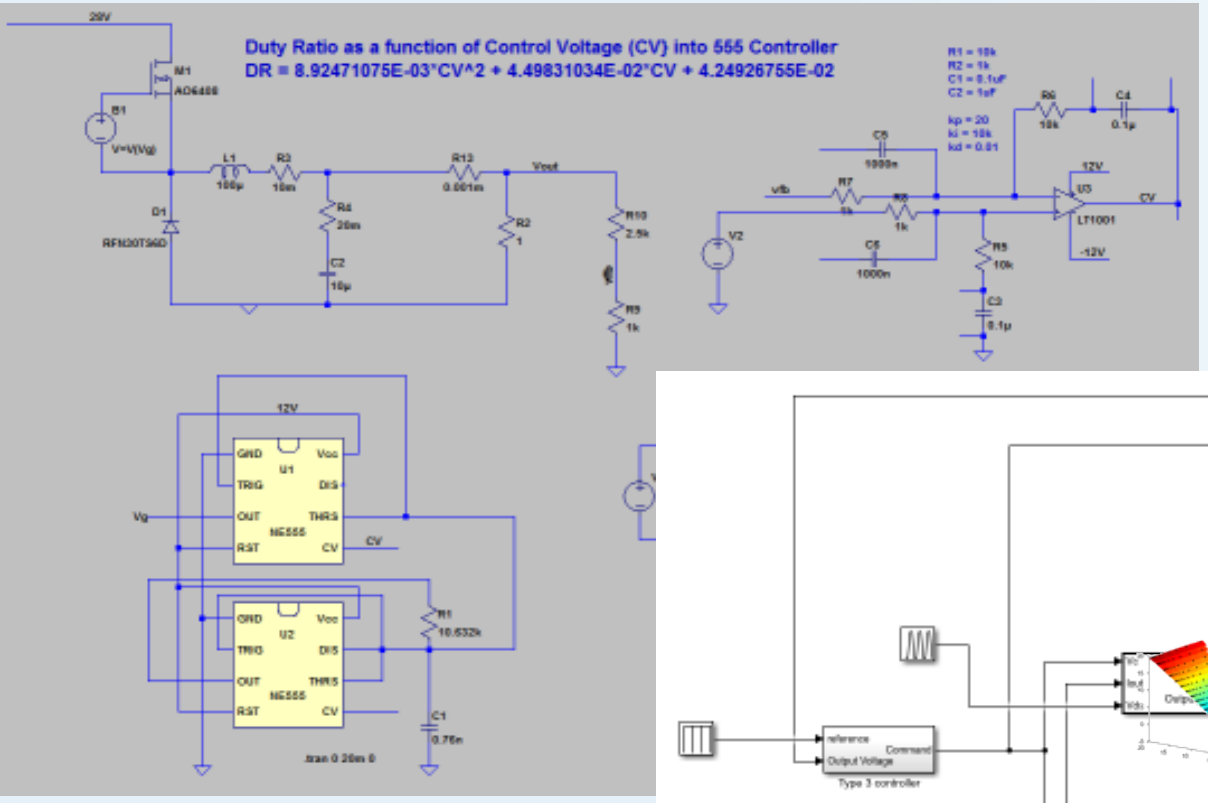


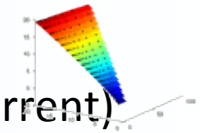
SIMULINK

Electrical Modeling – Power Converters

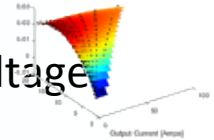
LTspice



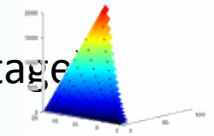
Output Voltage = (Duty Ratio, Output Current)



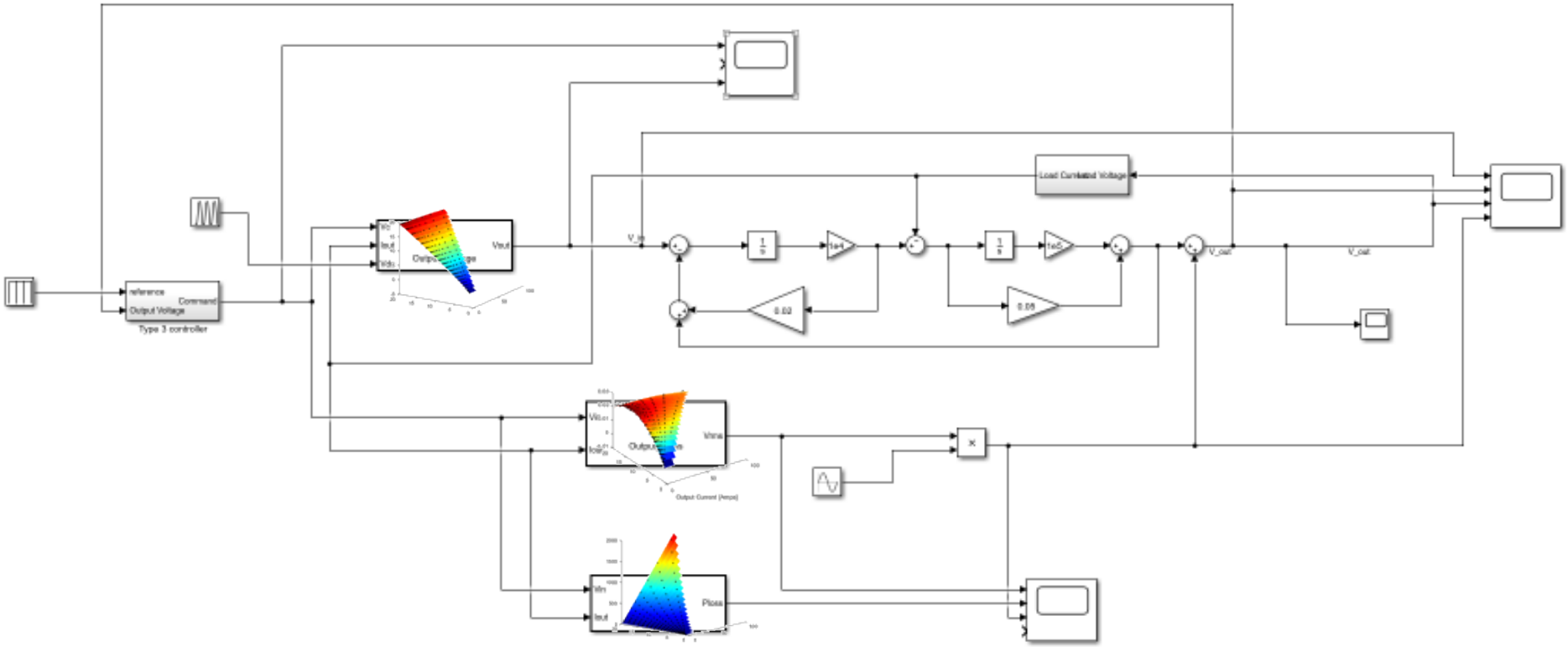
Output Voltage Ripple = (Duty Ratio, Output Voltage)



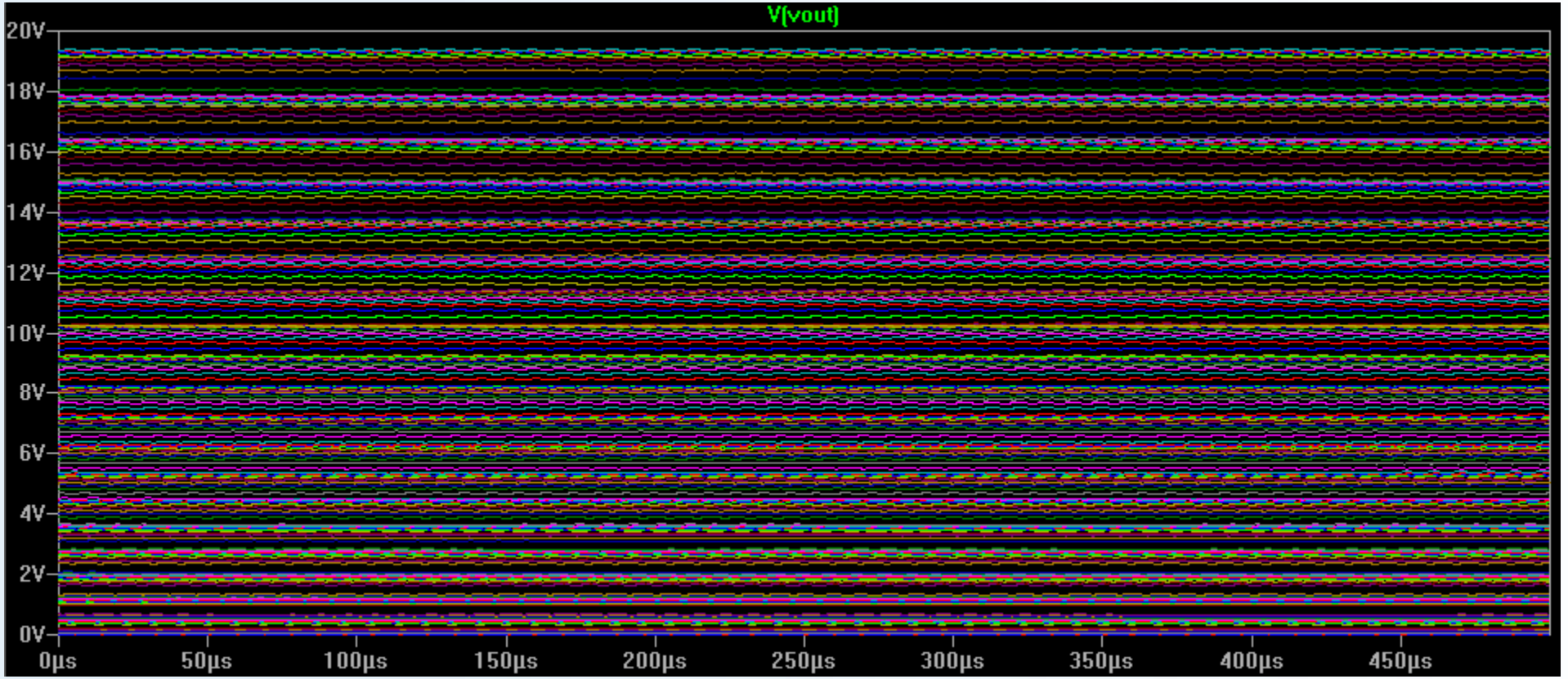
Power Loss = (Duty Ratio, Output Voltage)



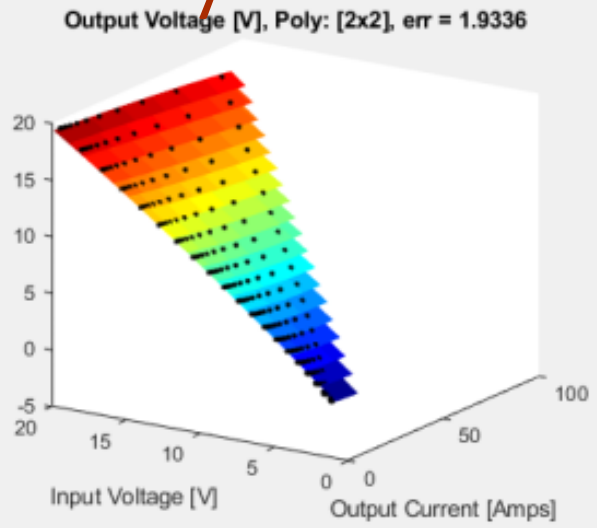
SIMULINK

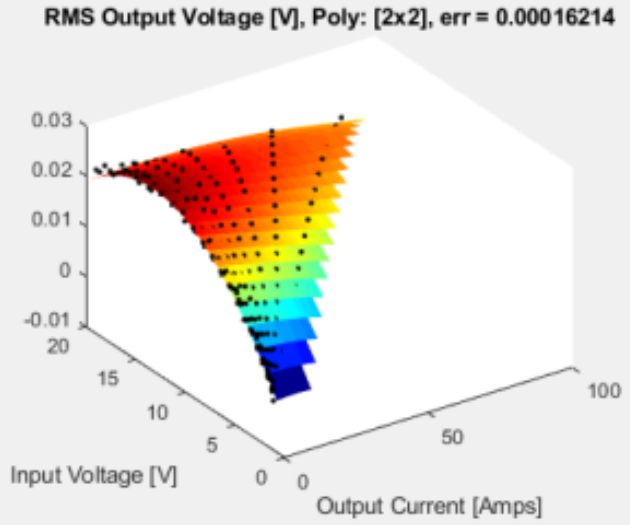


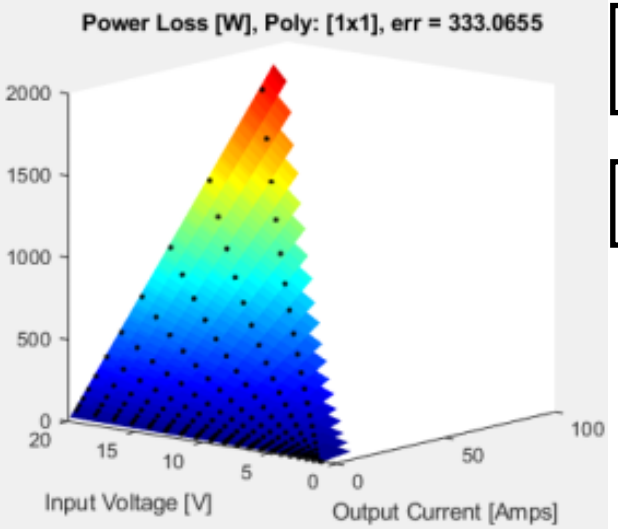
Sweeping Variables to extract Behavioral Parameters



Modeling Parameters as Multi-Dimensional Polynomials







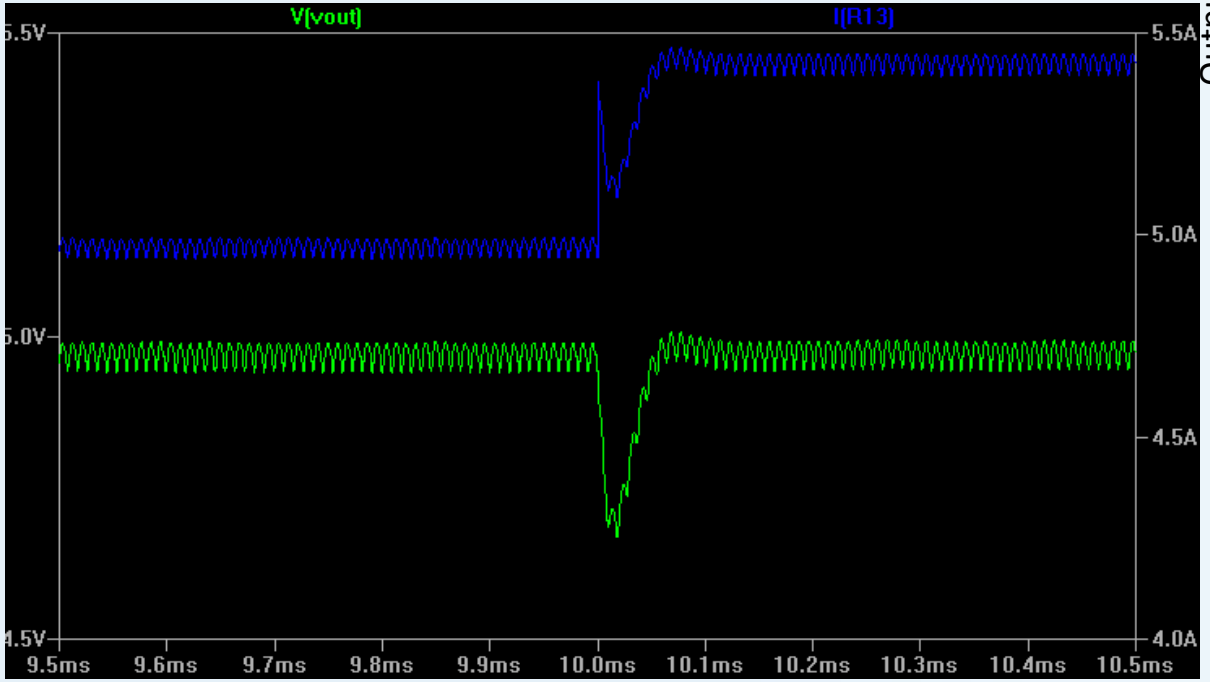
$$\begin{bmatrix} 1.127e\text{-}06 & 2.411e\text{-}04 & -6.790e\text{-}03 \\ -7.693e\text{-}05 & -4.359e\text{-}03 & 1.162e{+}00 \\ 1.015e\text{-}03 & -2.069e\text{-}02 & -1.222e{+}00 \end{bmatrix} \quad \begin{bmatrix} -3.219e\text{-}08 & 2.222e\text{-}06 & -1.667e\text{-}04 \\ 8.7346e\text{-}07 & -4.856e\text{-}05 & 4.504e\text{-}03 \\ -5.533e\text{-}06 & 1.205e\text{-}04 & -4.507e\text{-}03 \end{bmatrix}$$

$$\begin{bmatrix} 9.642e\text{-}01 & 4.549e\text{-}02 \\ 7.222e\text{-}01 & -9.500e\text{-}02 \end{bmatrix}$$

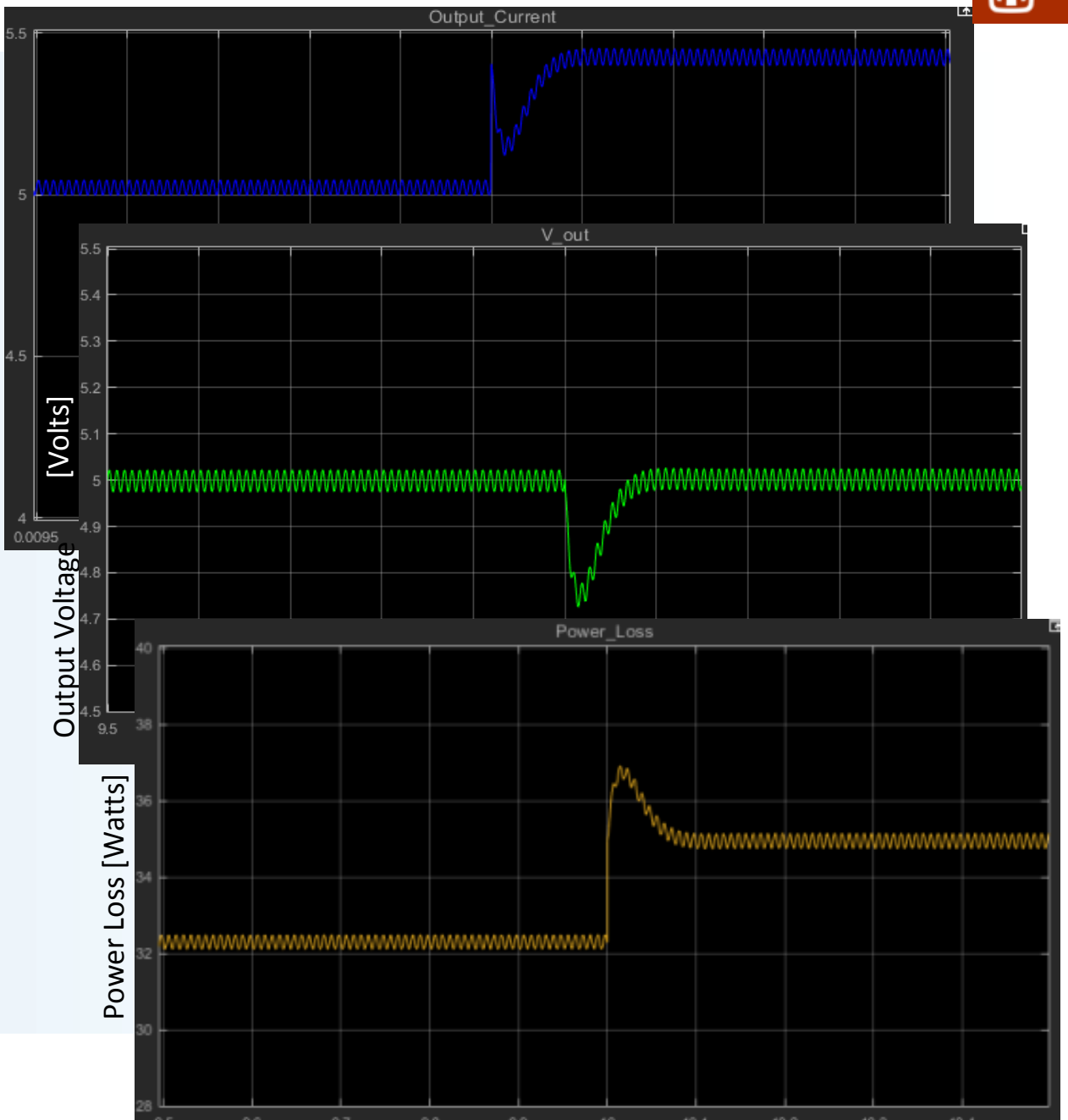
$$\begin{bmatrix} V_{in}^2 & V_{in} & 1 \end{bmatrix} \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} I_{out}^2 \\ I_{out} \\ 1 \end{bmatrix} = \begin{array}{l} A_{11}V_{in}^2I_{out}^2 + A_{12}V_{in}^2I_{out} + A_{13}V_{in}^2 + \\ A_{21}V_{in}I_{out}^2 + A_{22}V_{in}I_{out} + A_{23}V_{in} + \\ A_{31}I_{out}^2 + A_{32}I_{out} + A_{33} \end{array}$$

Power Converter Modeling Results

LTspice



SIMULINK

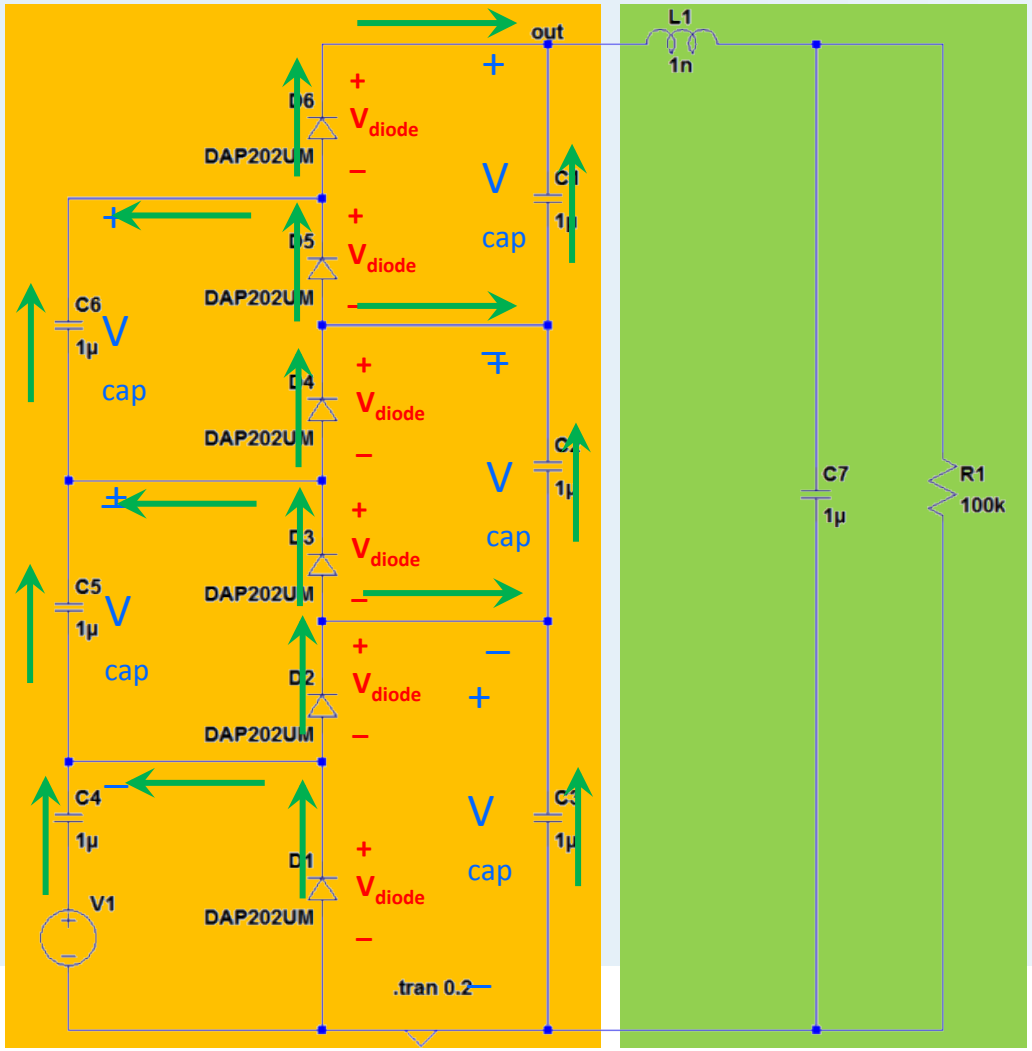


Electrical Modeling - Charge Pump

Charge Pump

LTspice

Load

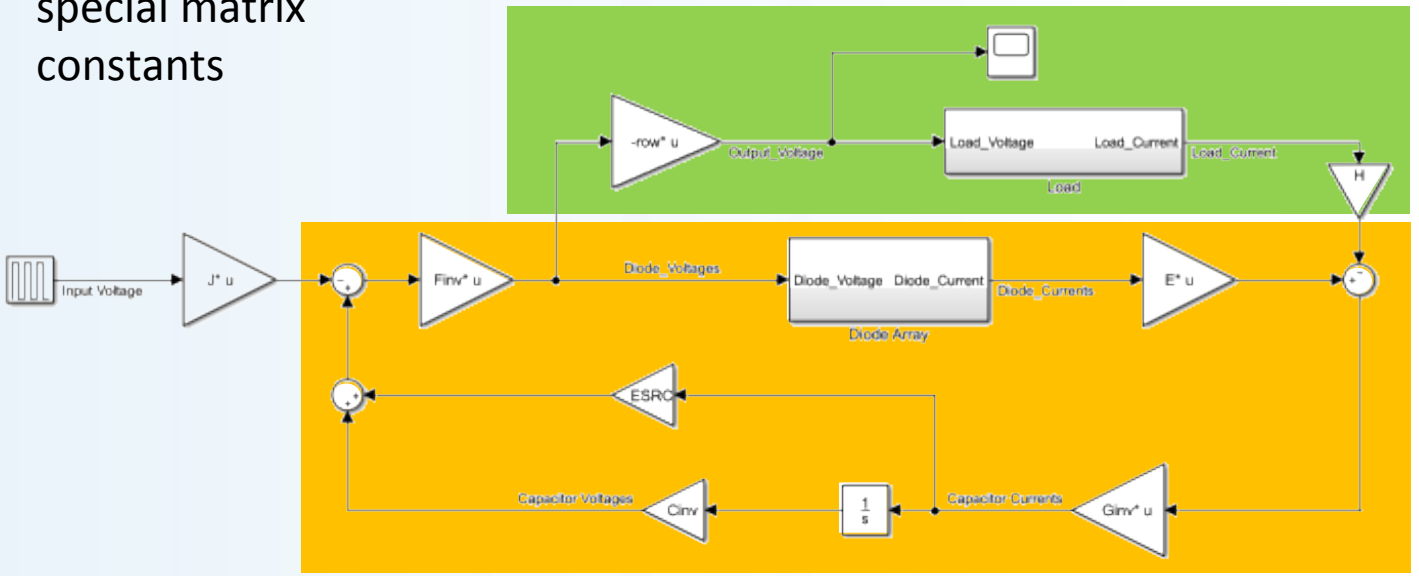


Model Topologies

Topologies with repetitions use special matrix constants

SIMULINK

Load

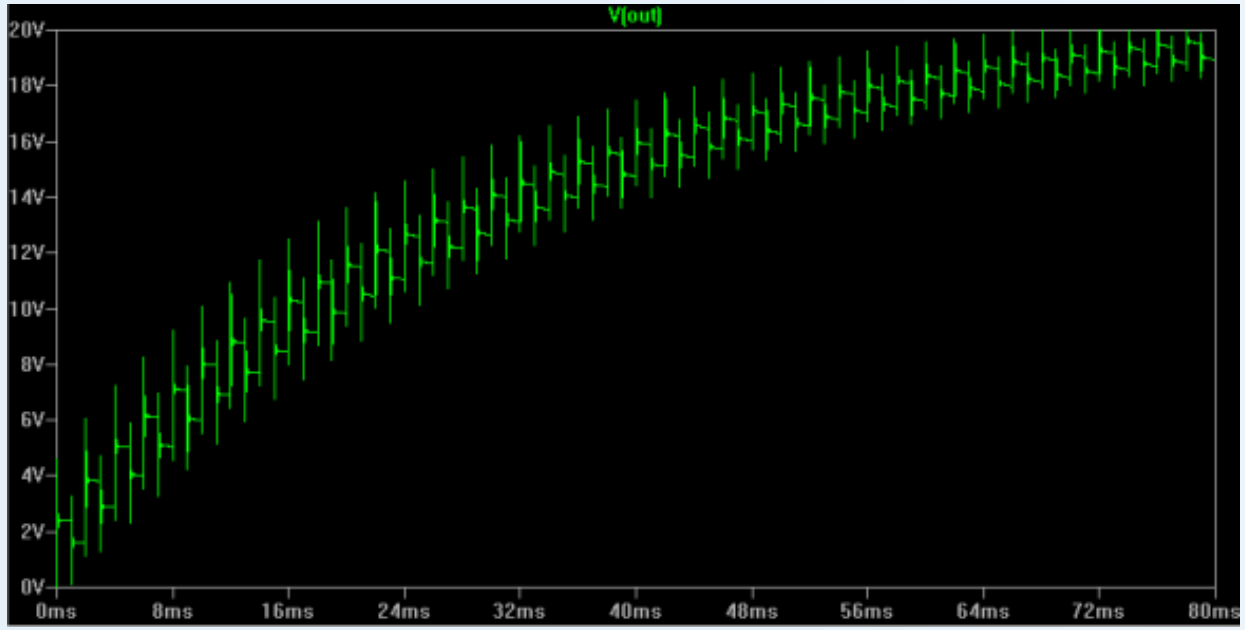


Charge Pump

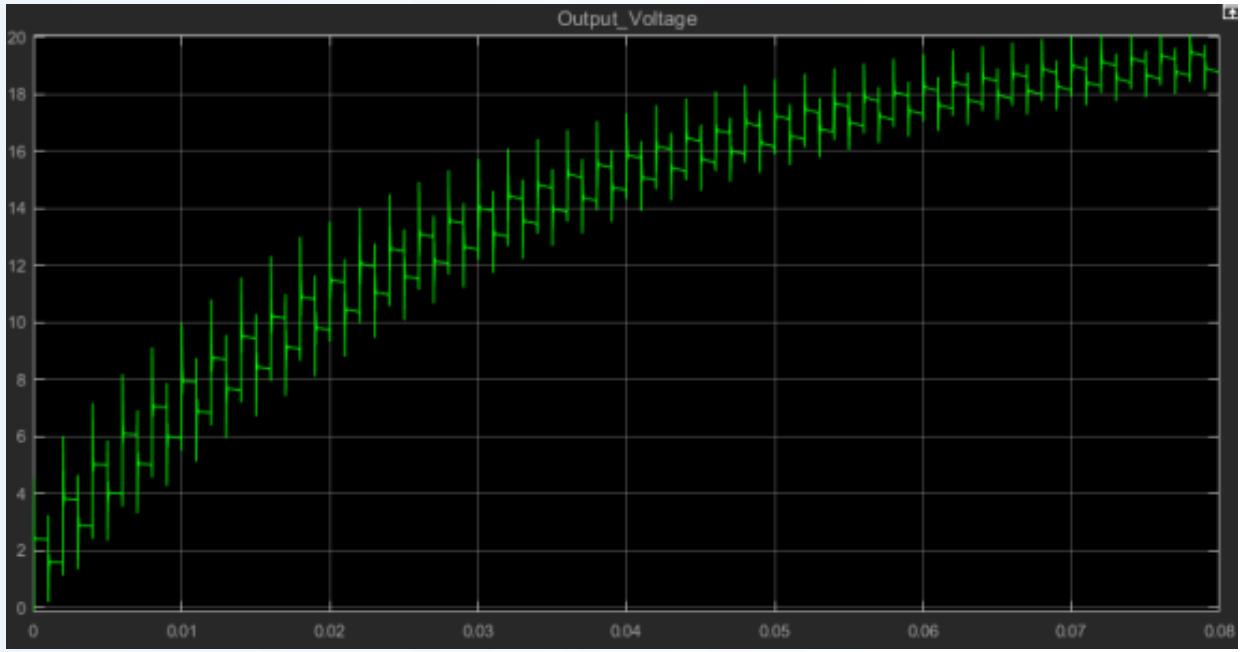
Charge Pump Modeling Results

Output Voltage

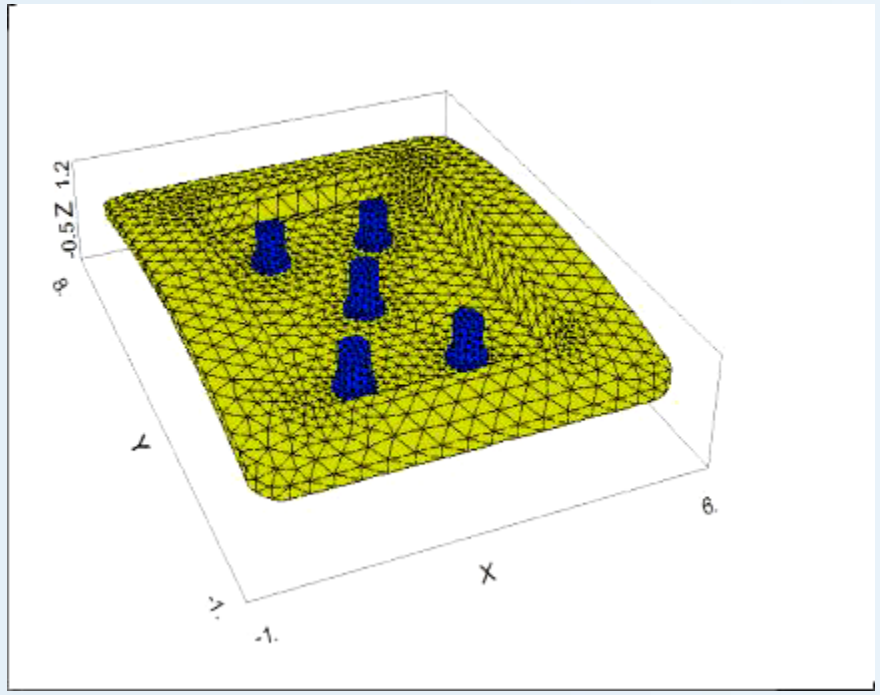
LTspice



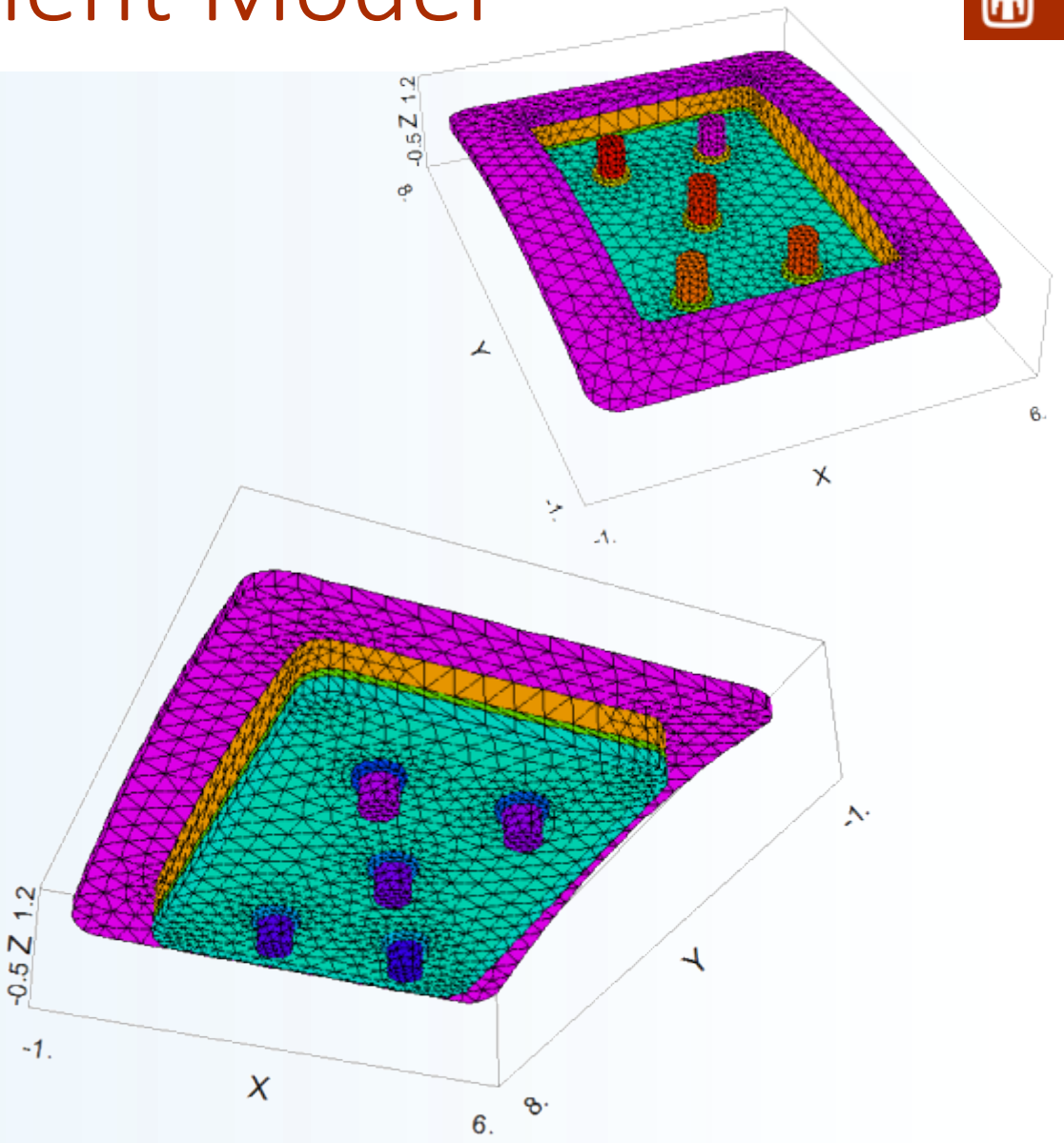
SIMULINK



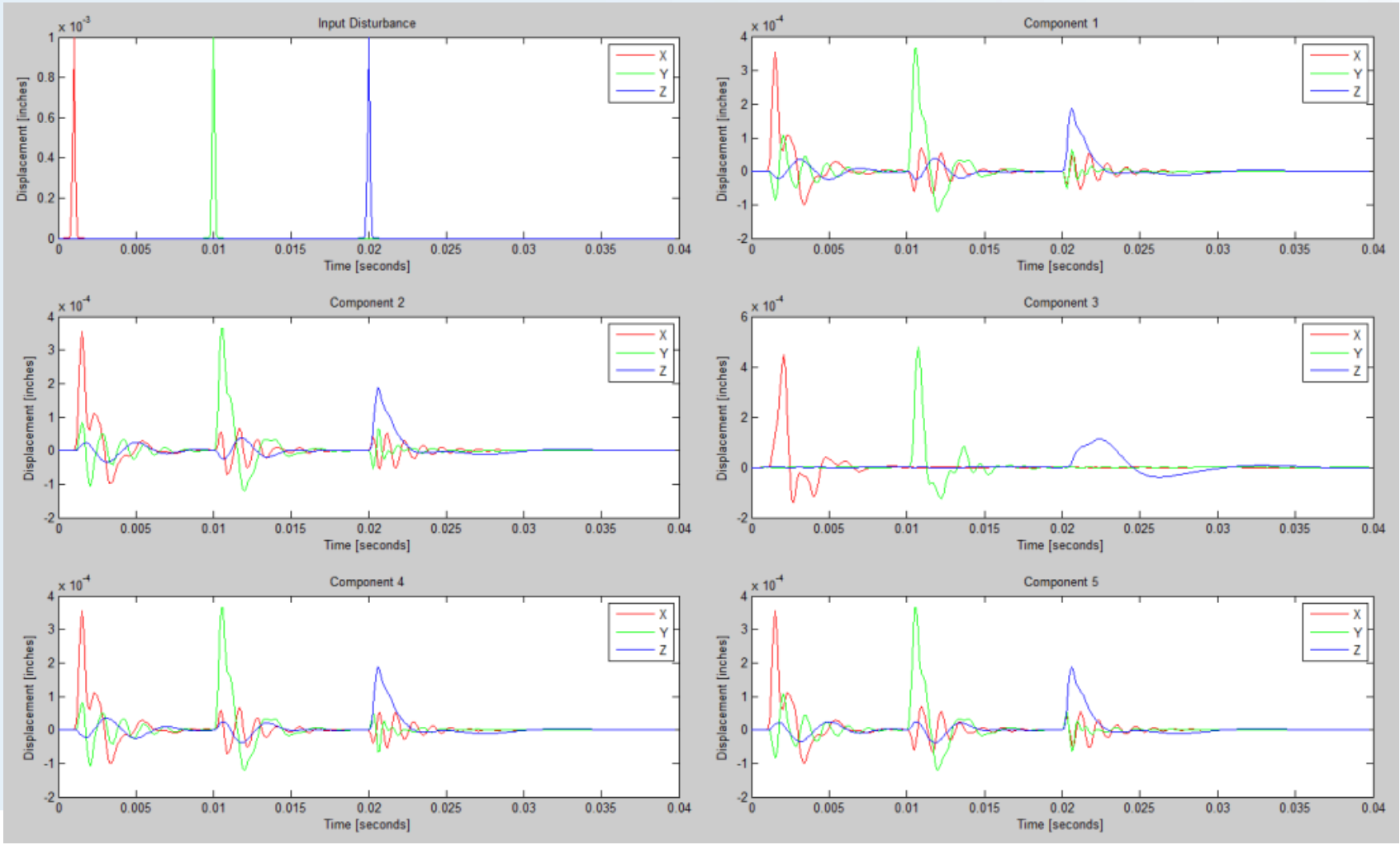
Physics Model - Finite Element Model

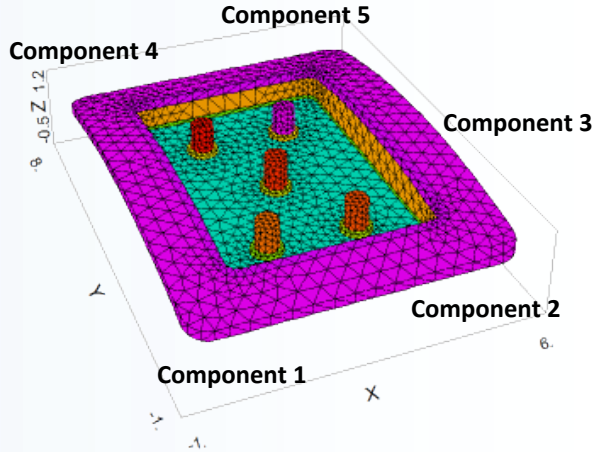


[Click on Video]

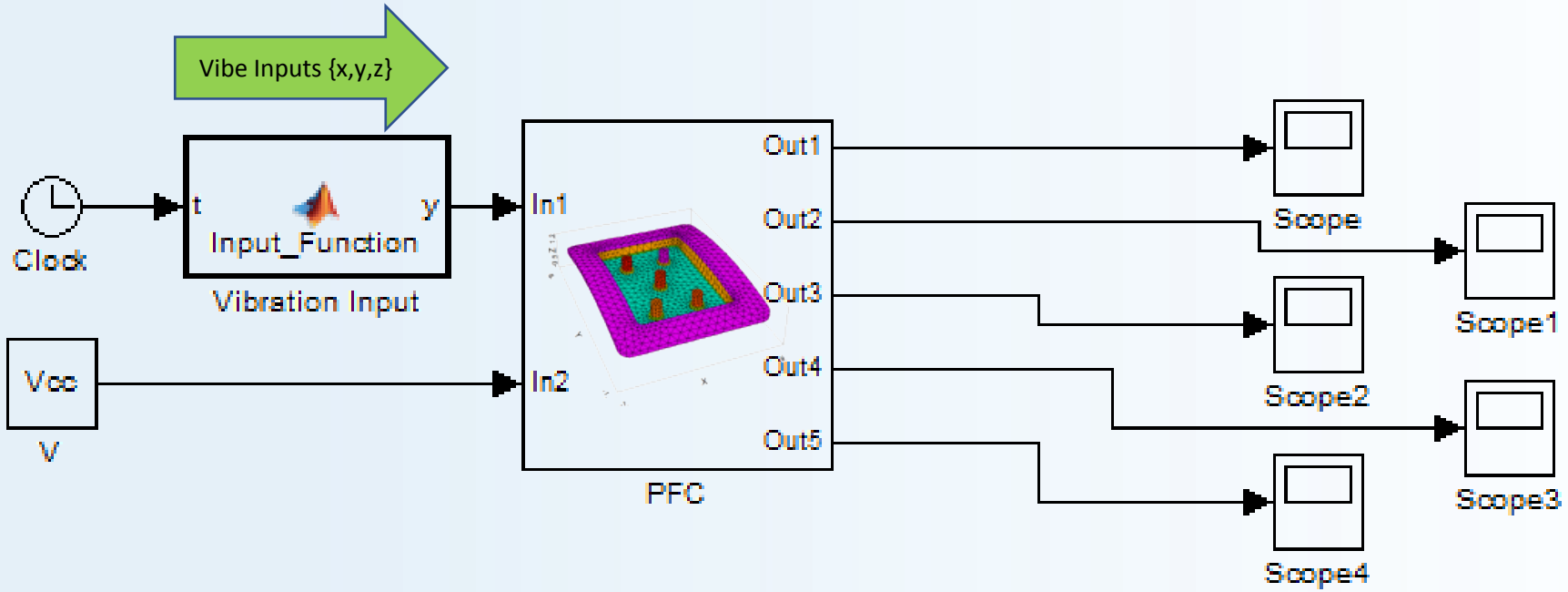


PFC Model – Shock/Vibe

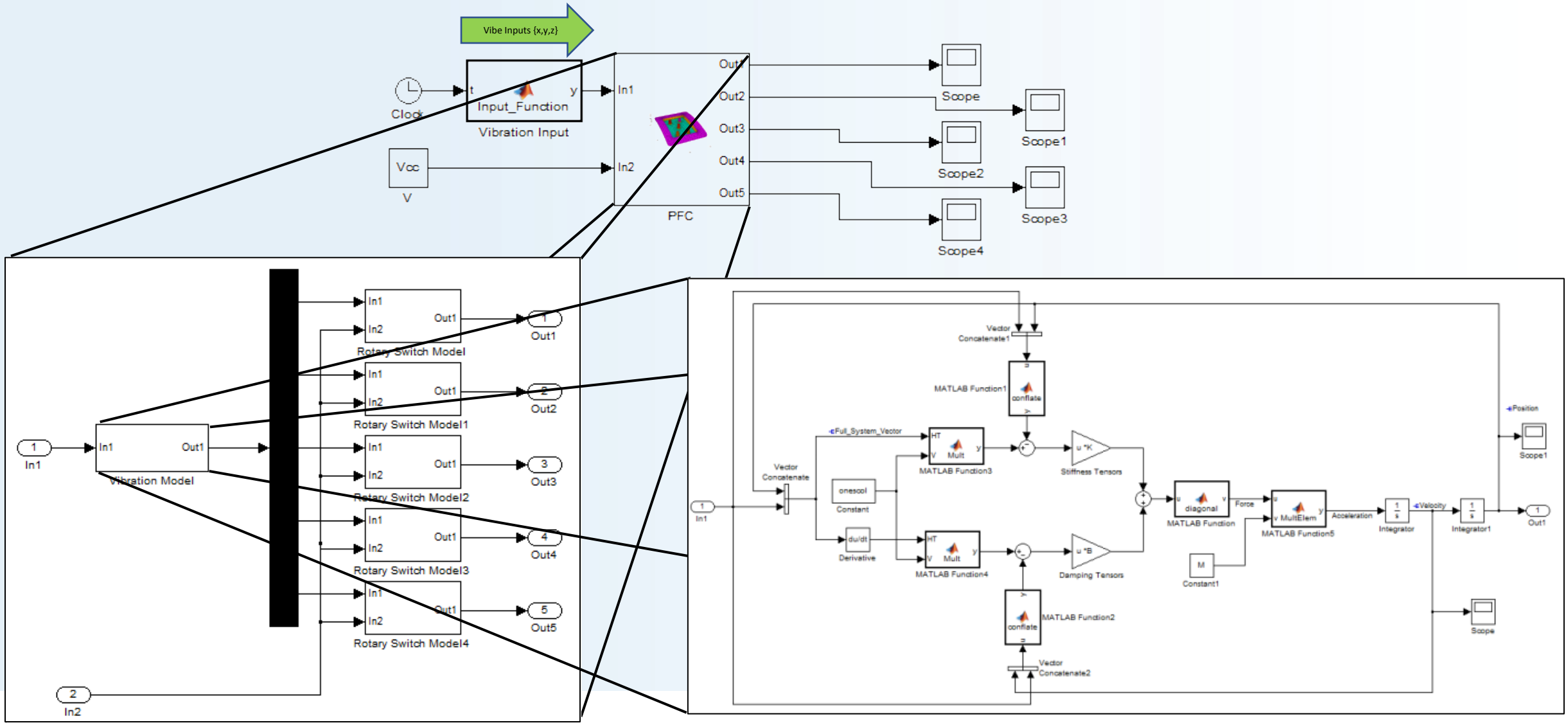




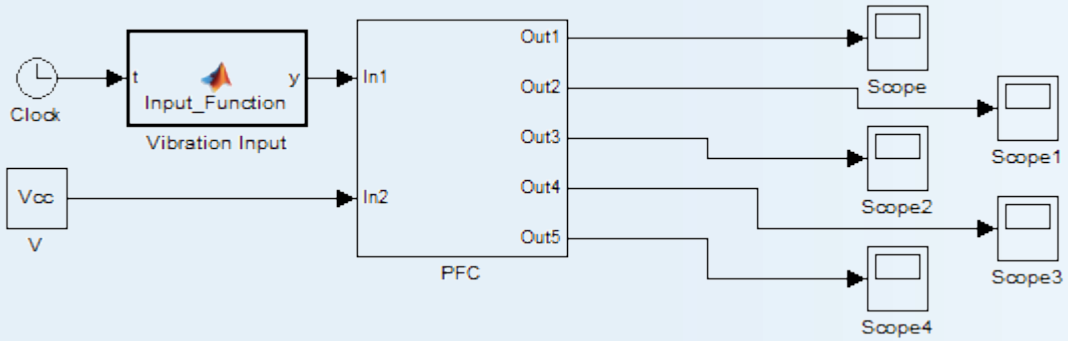
Top Level Simulink Model for Reduced Order Shock/Vibration

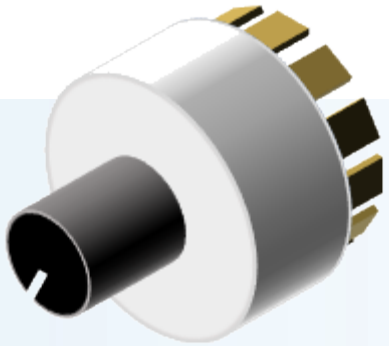


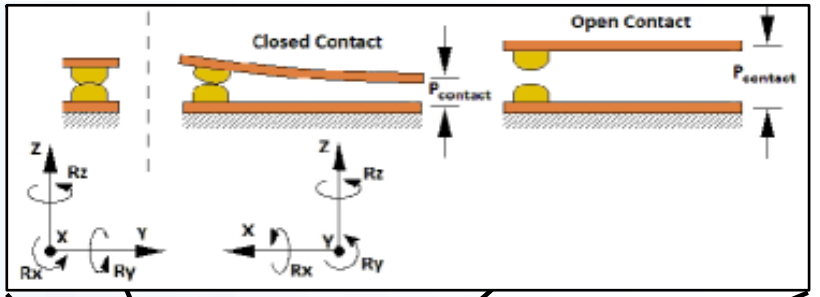
Simulink Model Reduced Order Shock/Vibration

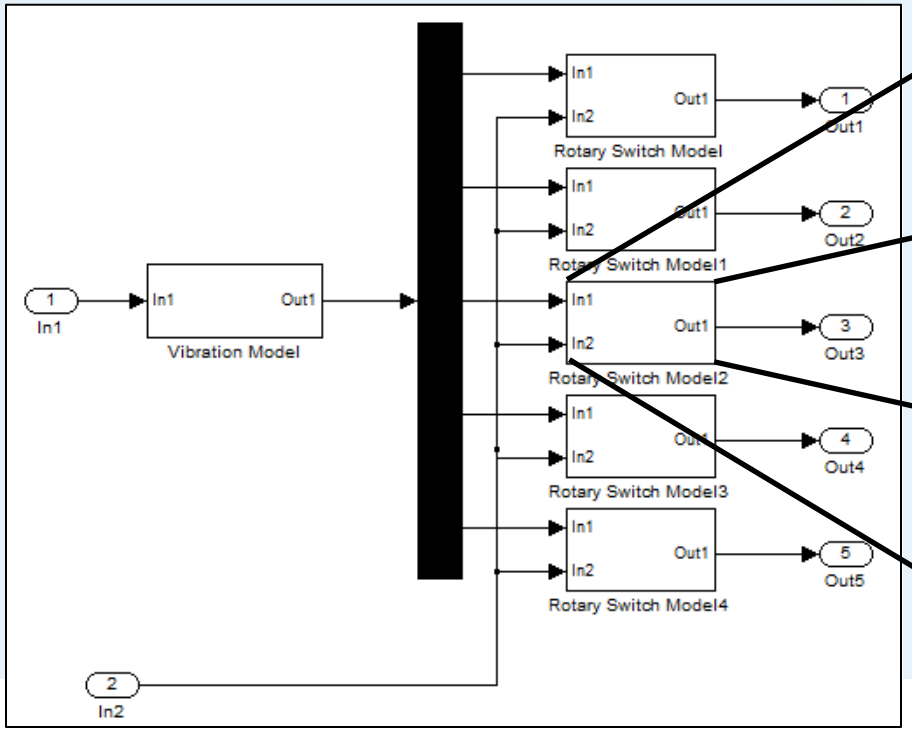


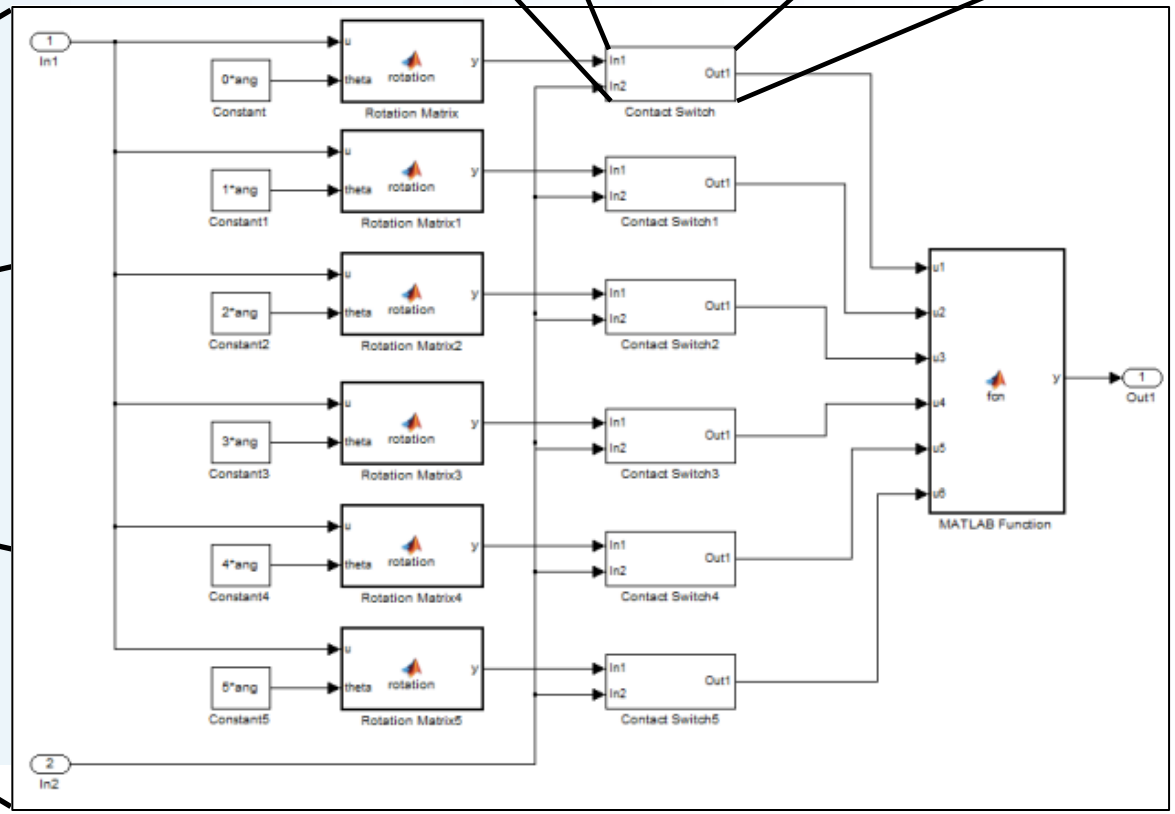
PFC - Simulink Model



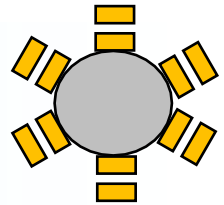




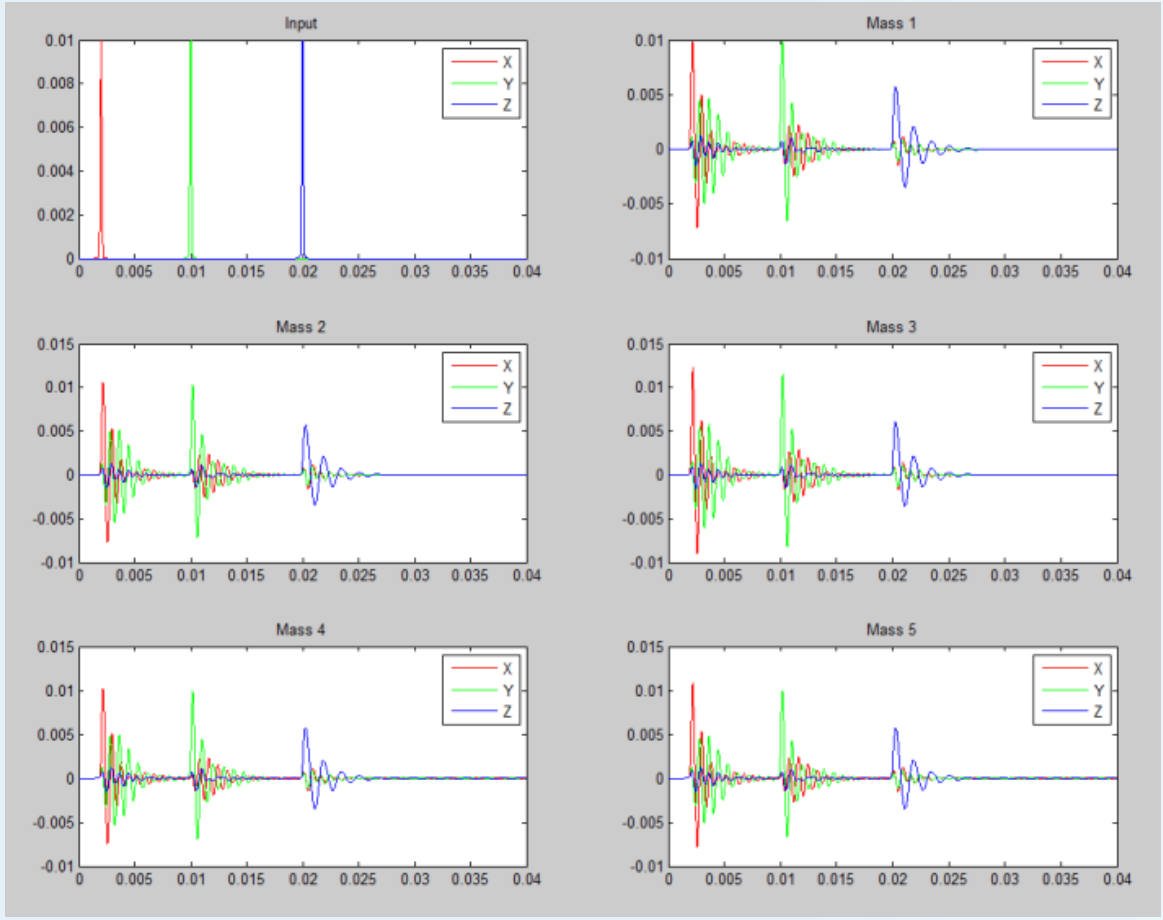




Simplified Five-Mass Model



Dynamics of each mass



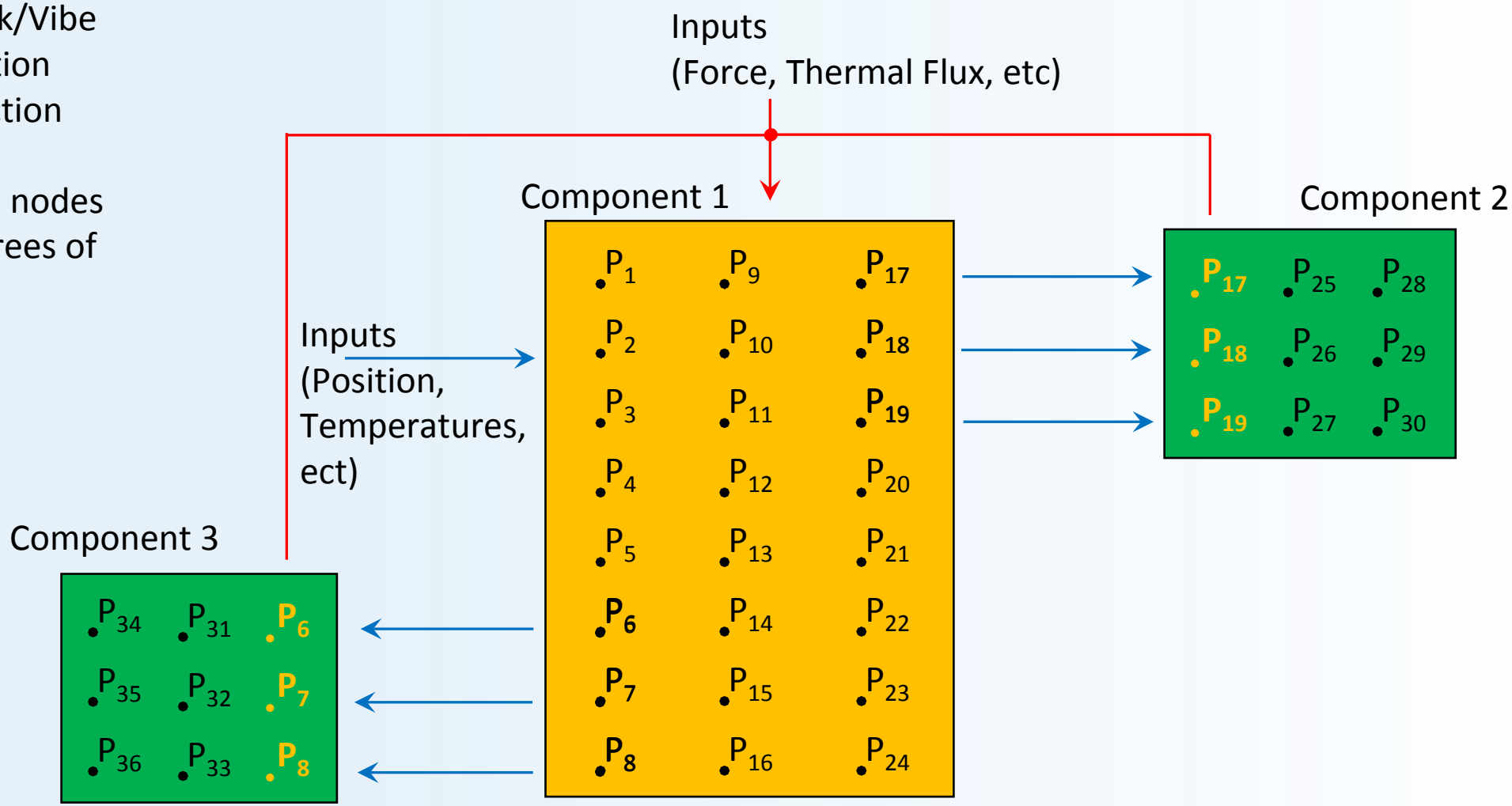
Acceleration at each connector on component 1
Each component has six contacts at 60° orientation

Connecting Linear Continuous Time Models

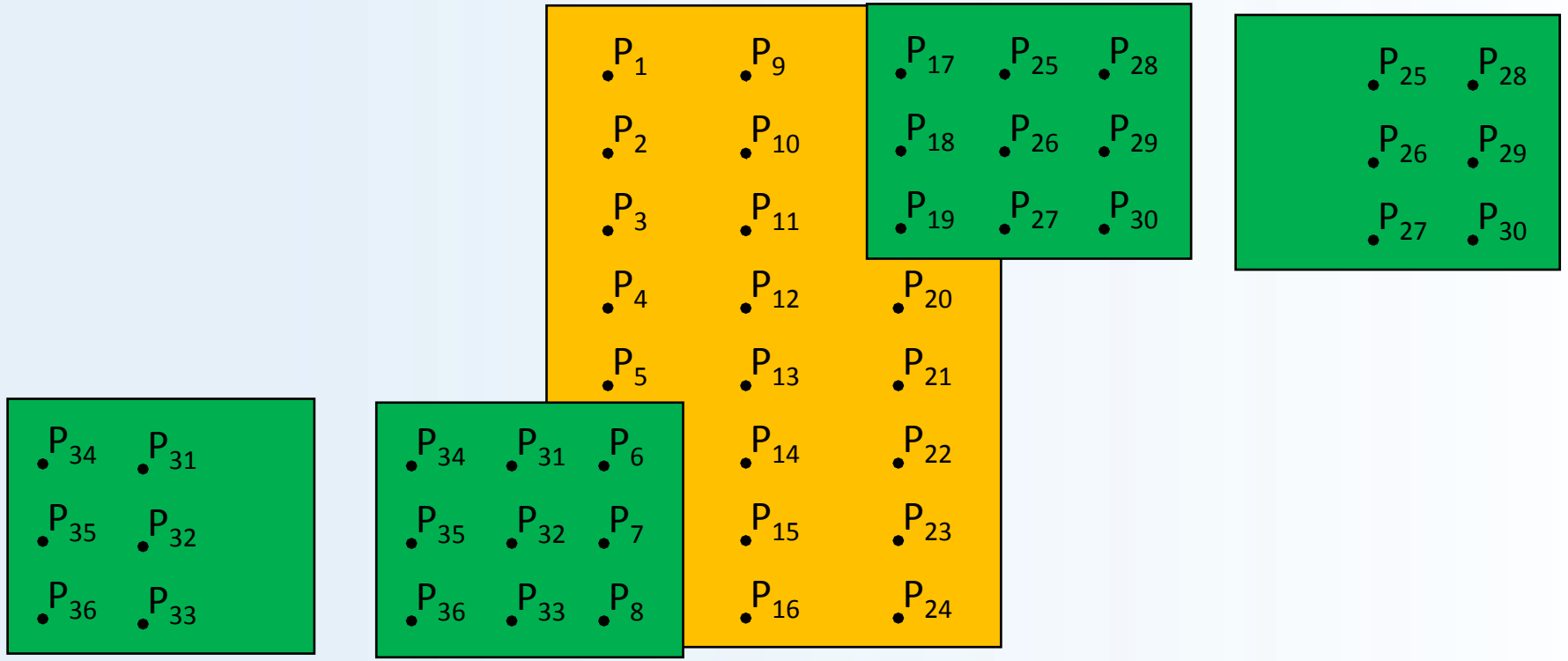
Mechanical Shock/Vibe
Thermal Conduction
Electrical Conduction

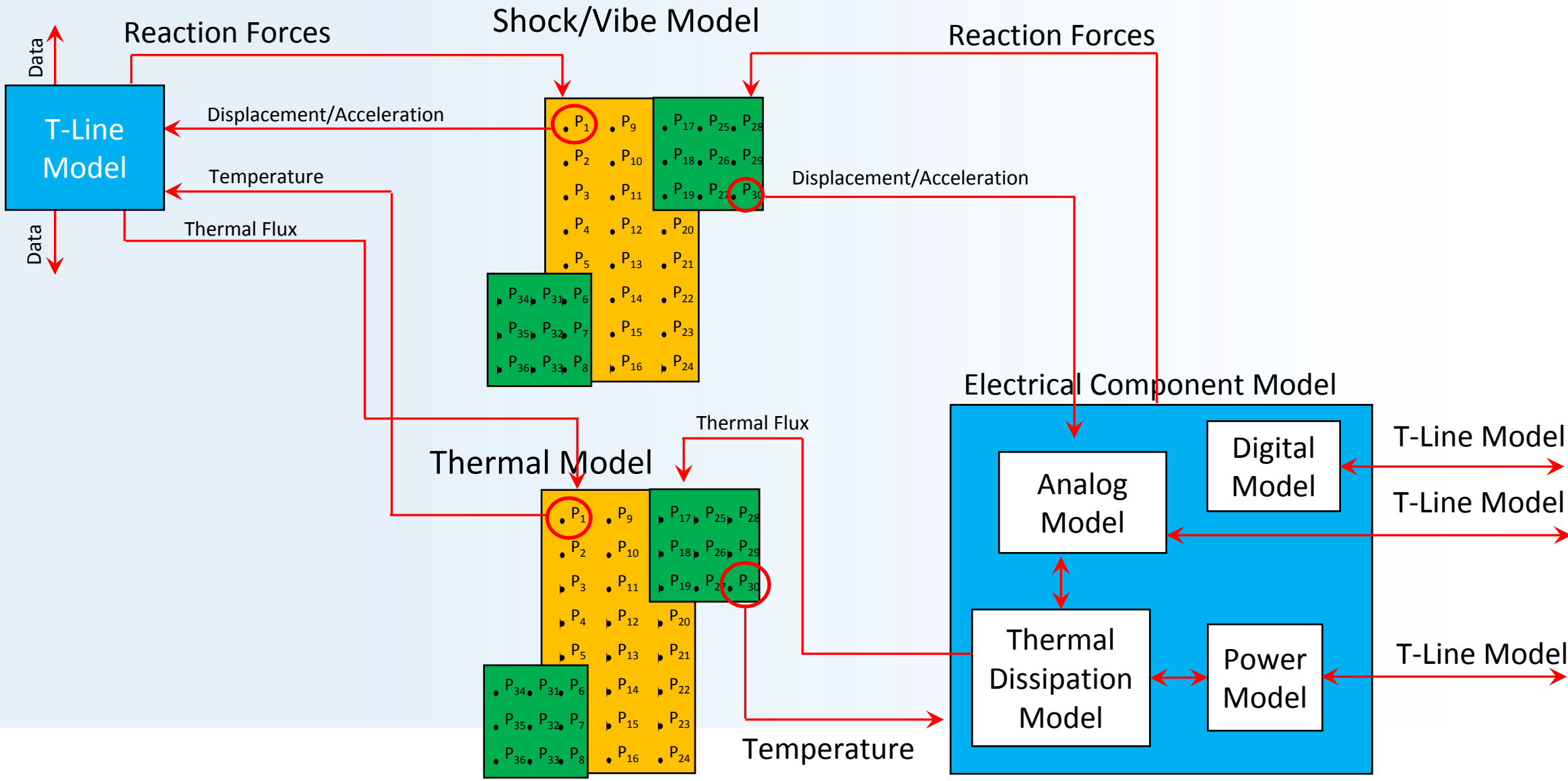
Points are spatial nodes with physics degrees of freedom:

- Temperature
- Displacement
- Voltage

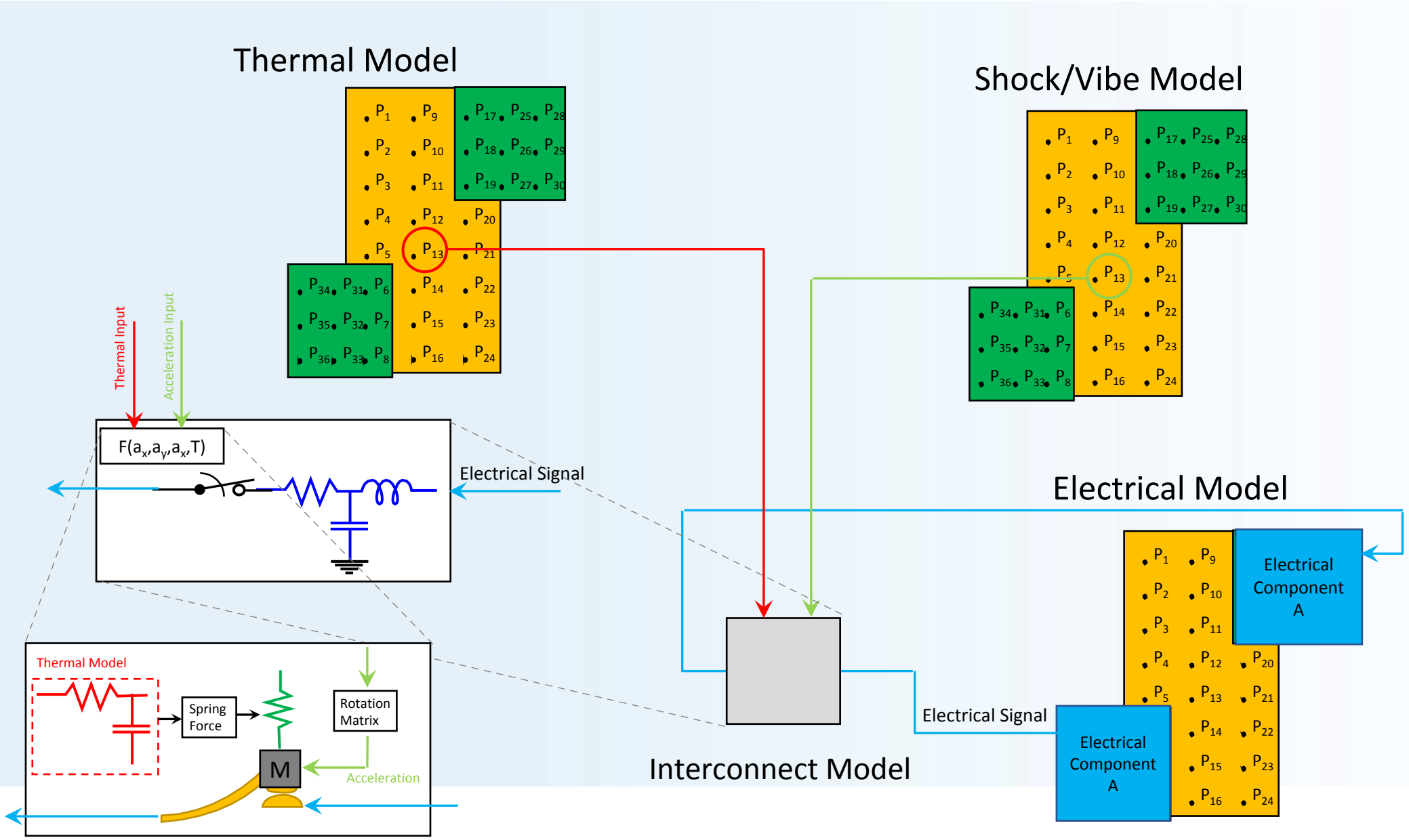


Connecting Linear Continuous Time Models

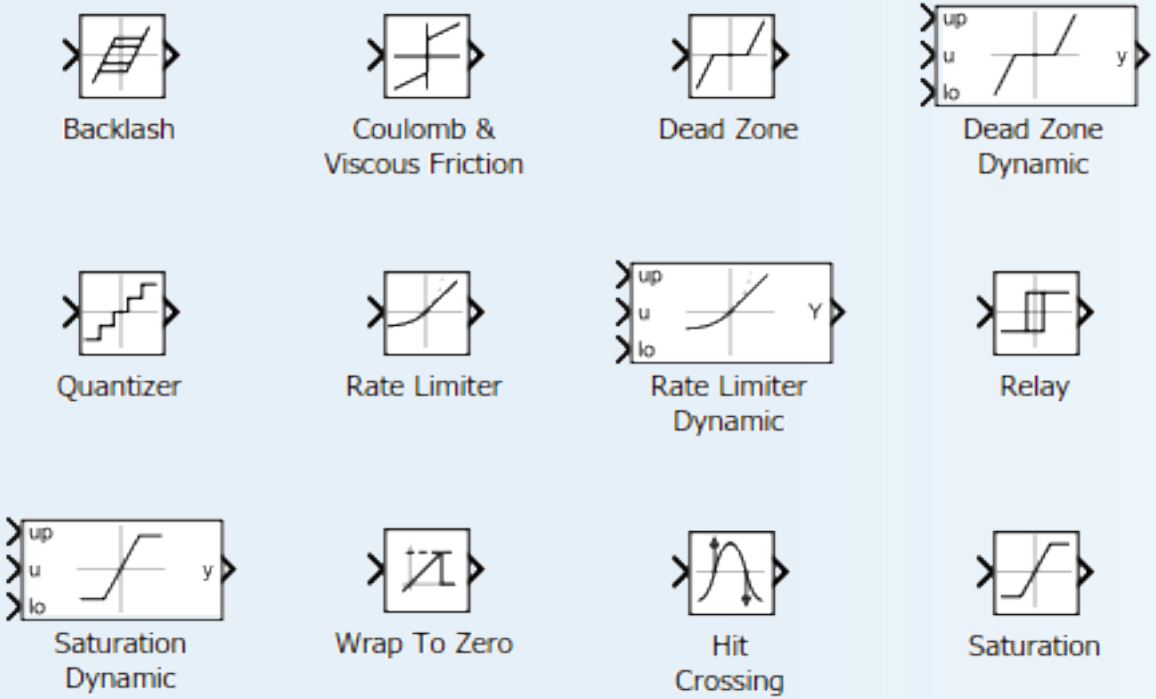



Shock/Vibe Model
Reaction Forces
Reaction Forces
Data
T-Line Model
Data
Displacement/Acceleration
Temperature
Thermal Flux
Displacement/Acceleration
Thermal Model
Thermal Flux
Electrical Component Model
Analog Model
Digital Model
Thermal Dissipation Model
Power Model
T-Line Model
T-Line Model
T-Line Model
Temperature

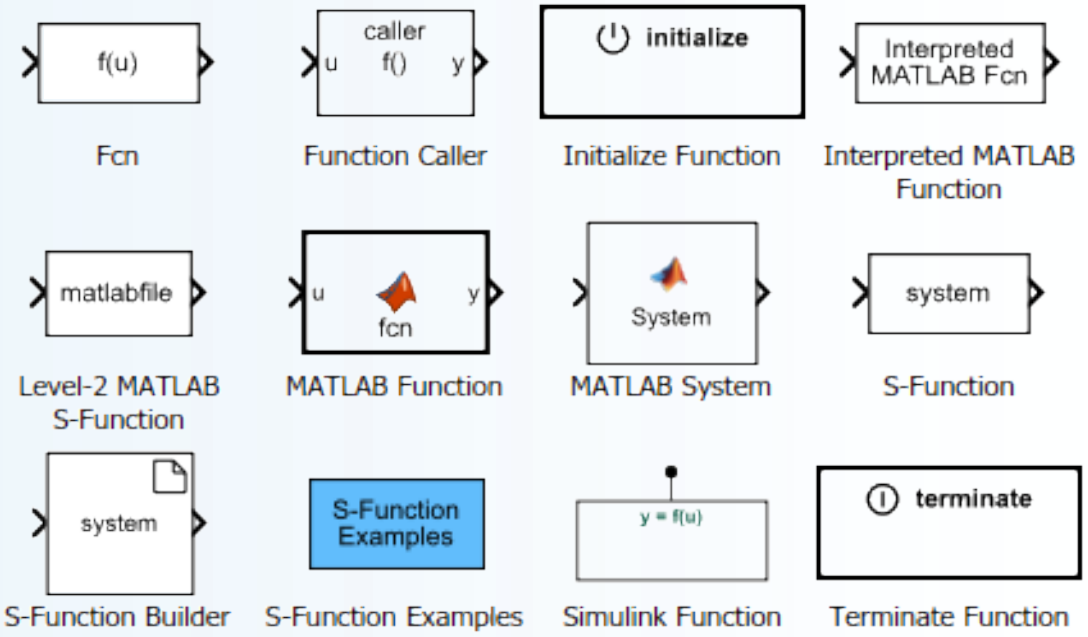
Modeling Interconnects in System Model



Modeling Nonlinearities



Can be added to existing linear models

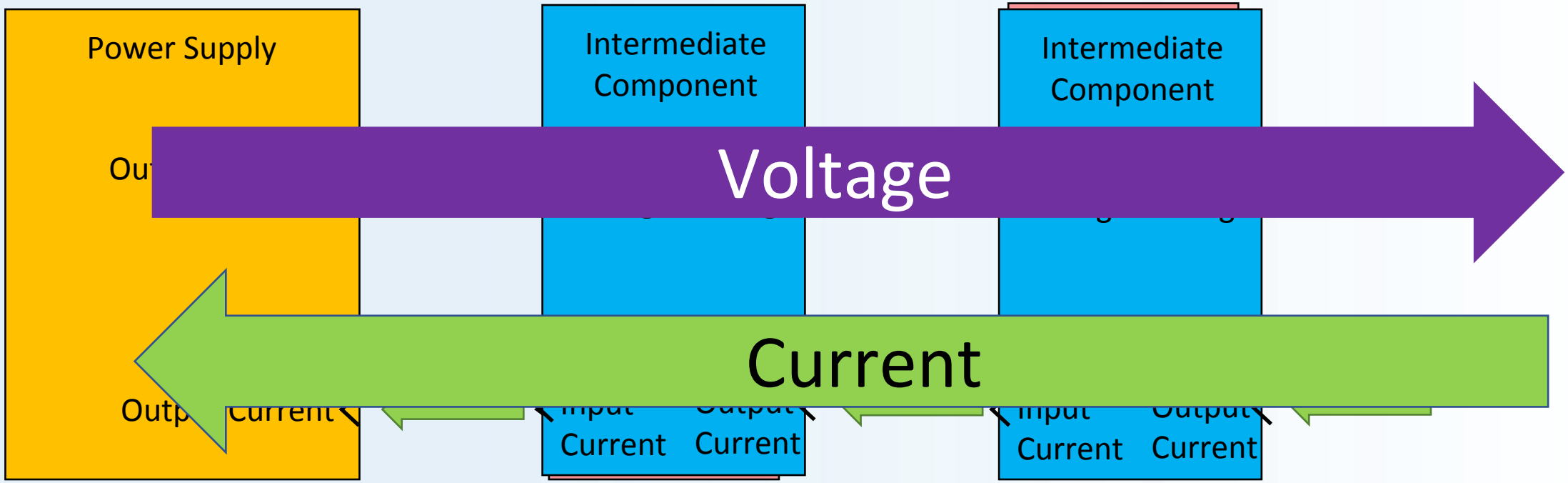


User-Defined, Custom models can be made

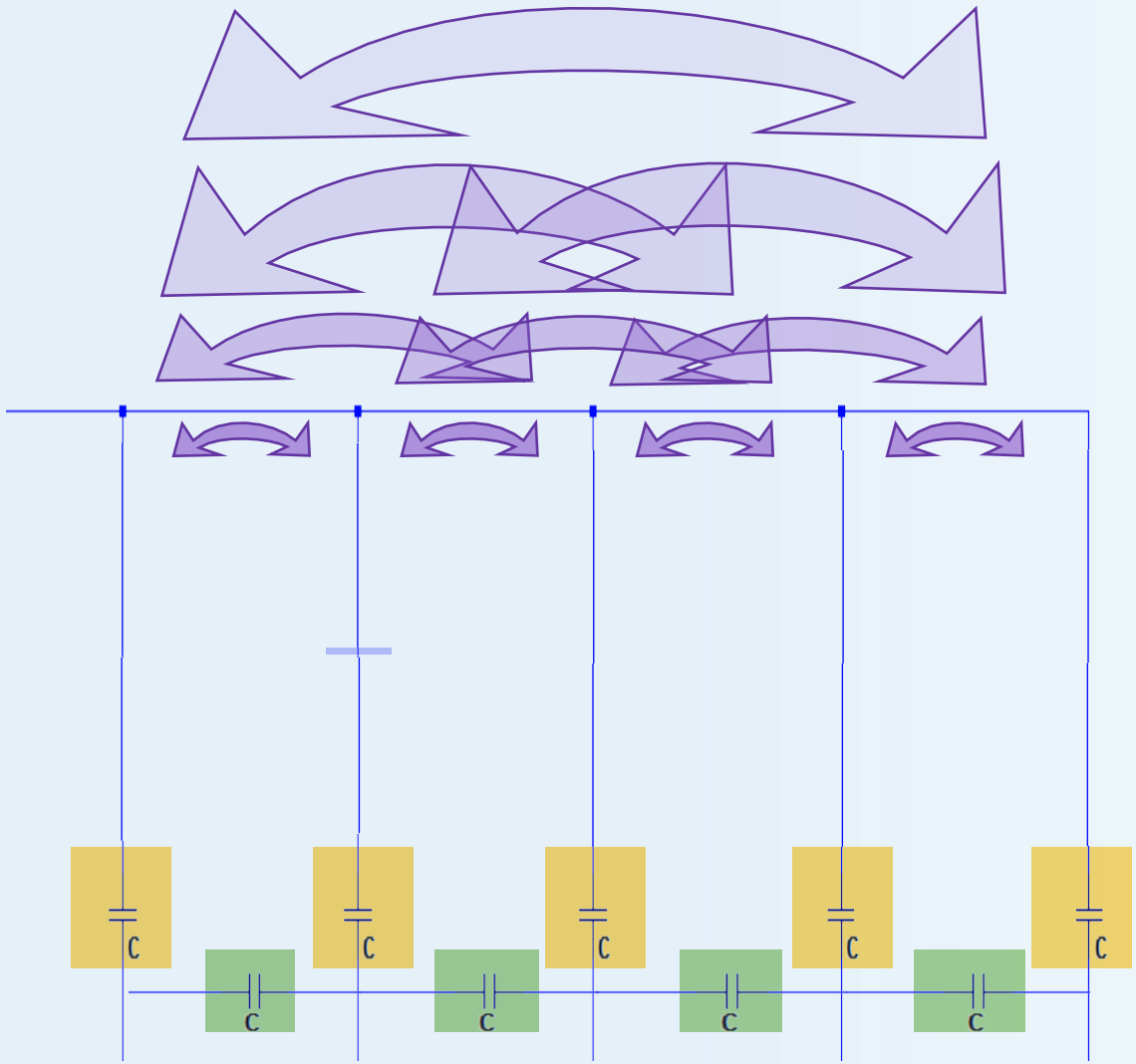
Electrical Modeling

- Analog
- Digital
- Power
  - Electrical - Thermal

Electrical Modeling



Capacitive Networks



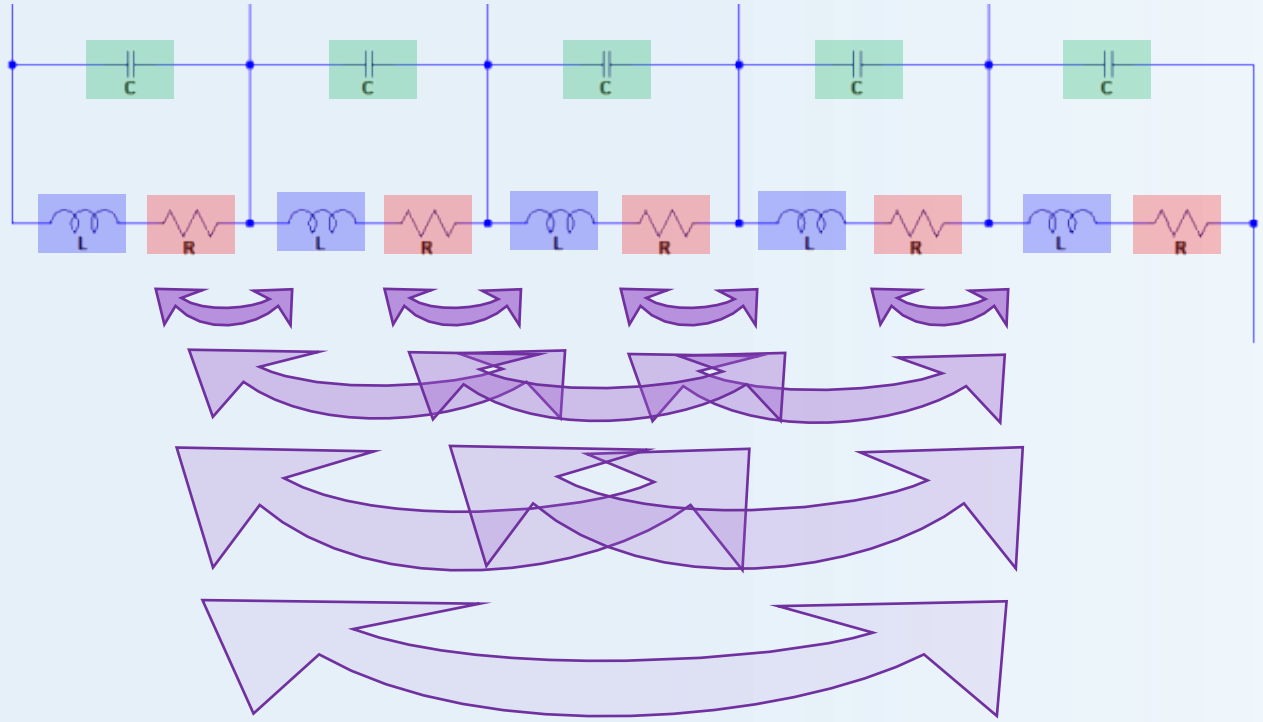
$$\begin{bmatrix} C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 \\ 0 & C_{23} & C_{33} & C_{34} & 0 \\ 0 & 0 & C_{34} & C_{44} & C_{45} \\ 0 & 0 & 0 & C_{45} & C_{55} \end{bmatrix}$$

$$\begin{bmatrix} C_{11}+C_{12} & -C_{12} & 0 & 0 & 0 \\ -C_{12} & C_{12}+C_{22}+C_{23} & -C_{23} & 0 & 0 \\ 0 & -C_{23} & C_{23}+C_{33}+C_{34} & -C_{34} & 0 \\ 0 & 0 & -C_{34} & C_{34}+C_{44}+C_{45} & -C_{45} \\ 0 & 0 & 0 & -C_{45} & C_{45}+C_{55} \end{bmatrix}$$

$$\begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{bmatrix}$$

$$\begin{bmatrix} L_{11} & L_{12} & L_{13} & L_{14} & L_{15} \\ L_{21} & L_{22} & L_{23} & L_{24} & L_{25} \\ L_{31} & L_{32} & L_{33} & L_{34} & L_{35} \\ L_{41} & L_{42} & L_{43} & L_{44} & L_{45} \\ L_{51} & L_{52} & L_{53} & L_{54} & L_{55} \end{bmatrix}$$

Inductive Networks



$$\begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{bmatrix}$$

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{bmatrix} \qquad \begin{bmatrix} -C_1 & 0 & 0 & 0 & 0 \\ C_1 & -C_2 & 0 & 0 & 0 \\ 0 & C_2 & -C_3 & 0 & 0 \\ 0 & 0 & C_3 & -C_4 & 0 \\ 0 & 0 & 0 & C_4 & -C_5 \end{bmatrix}$$

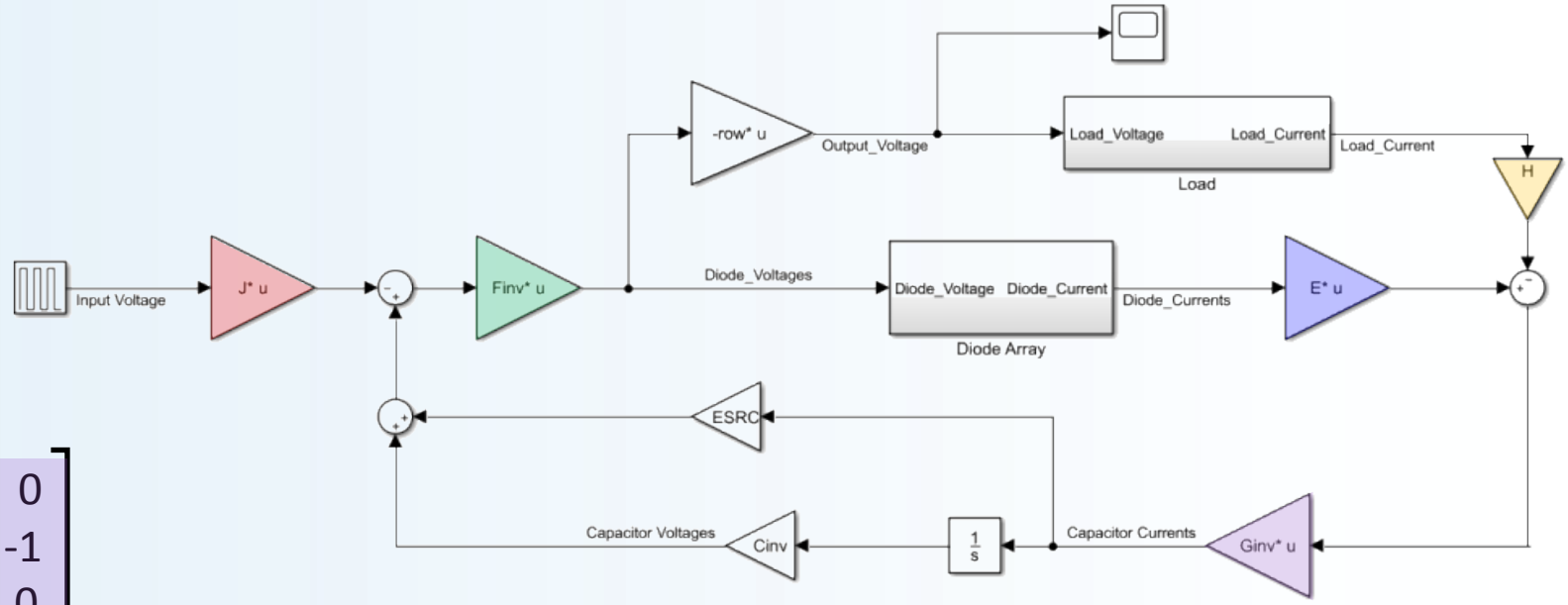
$$\begin{bmatrix} L_{11} & L_{12} & L_{13} & L_{14} & L_{15} \\ L_{21} & L_{22} & L_{23} & L_{24} & L_{25} \\ L_{31} & L_{32} & L_{33} & L_{34} & L_{35} \\ L_{41} & L_{42} & L_{43} & L_{44} & L_{45} \\ L_{51} & L_{52} & L_{53} & L_{54} & L_{55} \end{bmatrix}$$

Topologically Derived Charge Pump Constants

$$E = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad J = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad H = \begin{bmatrix} 0 \\ -1 \\ 0 \\ -1 \\ 0 \\ -1 \end{bmatrix}$$

$$F = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \quad F^{-1} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ -1 & -1 & 1 & 0 & 0 & 0 \\ 1 & 1 & -1 & 1 & 0 & 0 \\ -1 & -1 & 1 & -1 & 1 & 0 \\ 1 & 1 & -1 & 1 & -1 & 1 \end{bmatrix}$$

$$G = \begin{bmatrix} -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} \quad G^{-1} = \begin{bmatrix} -1 & 0 & -1 & 0 & -1 & 0 \\ 0 & -1 & 0 & -1 & 0 & -1 \\ 0 & 0 & -1 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 & 0 & -1 \\ 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$



Electrical Modeling – Digital FPA Model Example

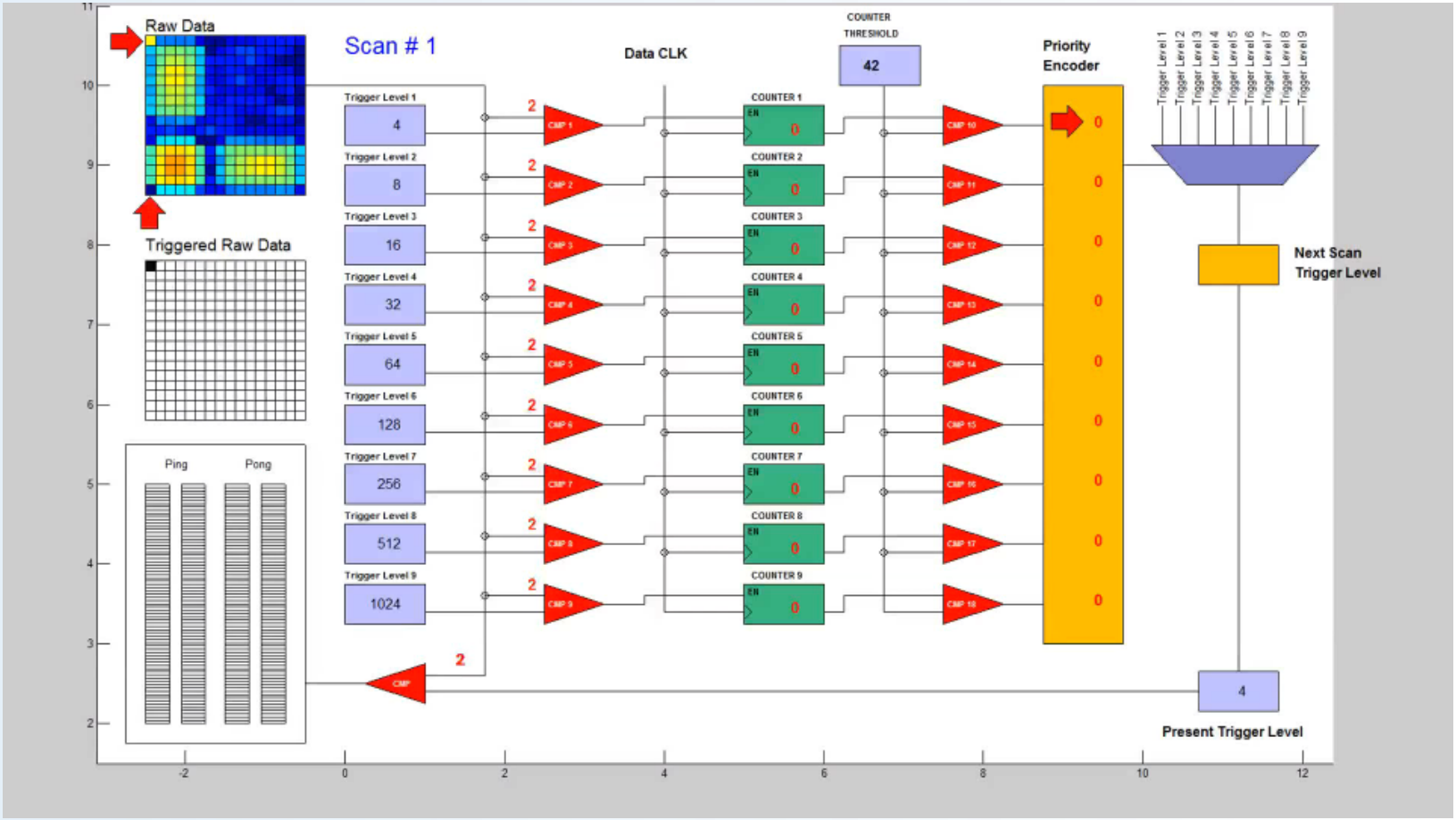
Modeled components:

- Configuration Registers
- Digital Signal Processors
- Ping-Pong SRAM Memories
- Counters
- Comparators
- Latches
- Other state machines

Functions:

- High-pass/low –pass image filtering
- Auto trigger threshold shifting
- Commandable windows
  - Force trigger
  - Mask
  - Return to normal
- Persistence latching
- Data Prioritization modes
- Noise threshold pointers

A Matlab model was made of a Sandia-designed High Speed Focal Plane Array (FPA)

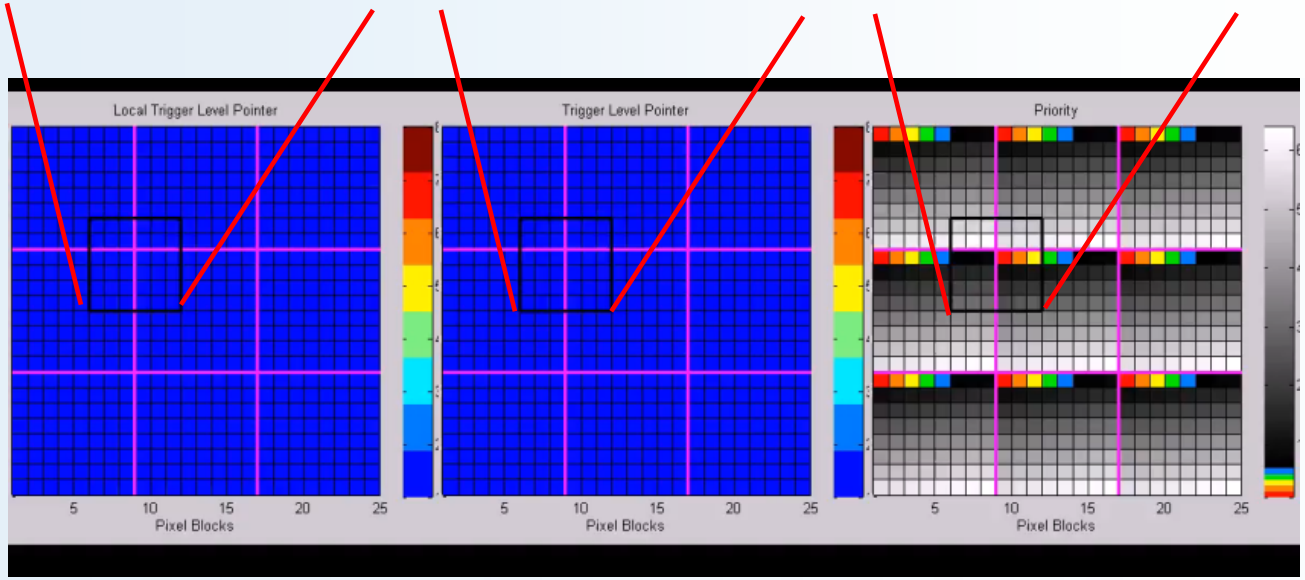


[Click on Video]

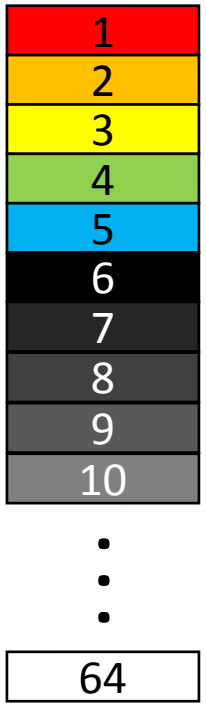
Electrical Modeling - Digital

384 x 384 Pixels,
2304 Digital Signal Processors

Entire Focal Plane array
1536 x 1536 Pixels



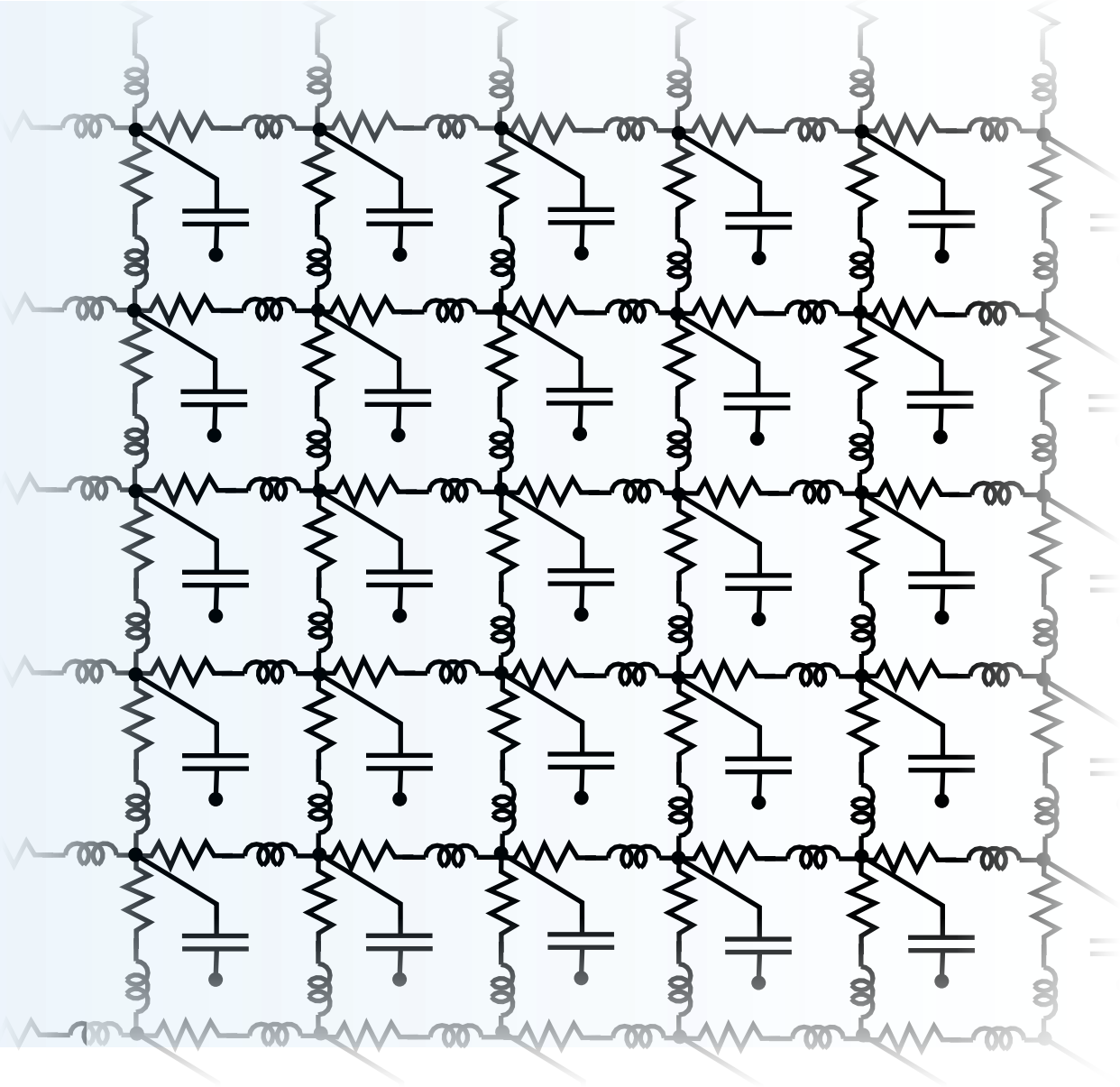
Top 5 Prioritized DSPs



[Click on Video]

Electrical Conduction

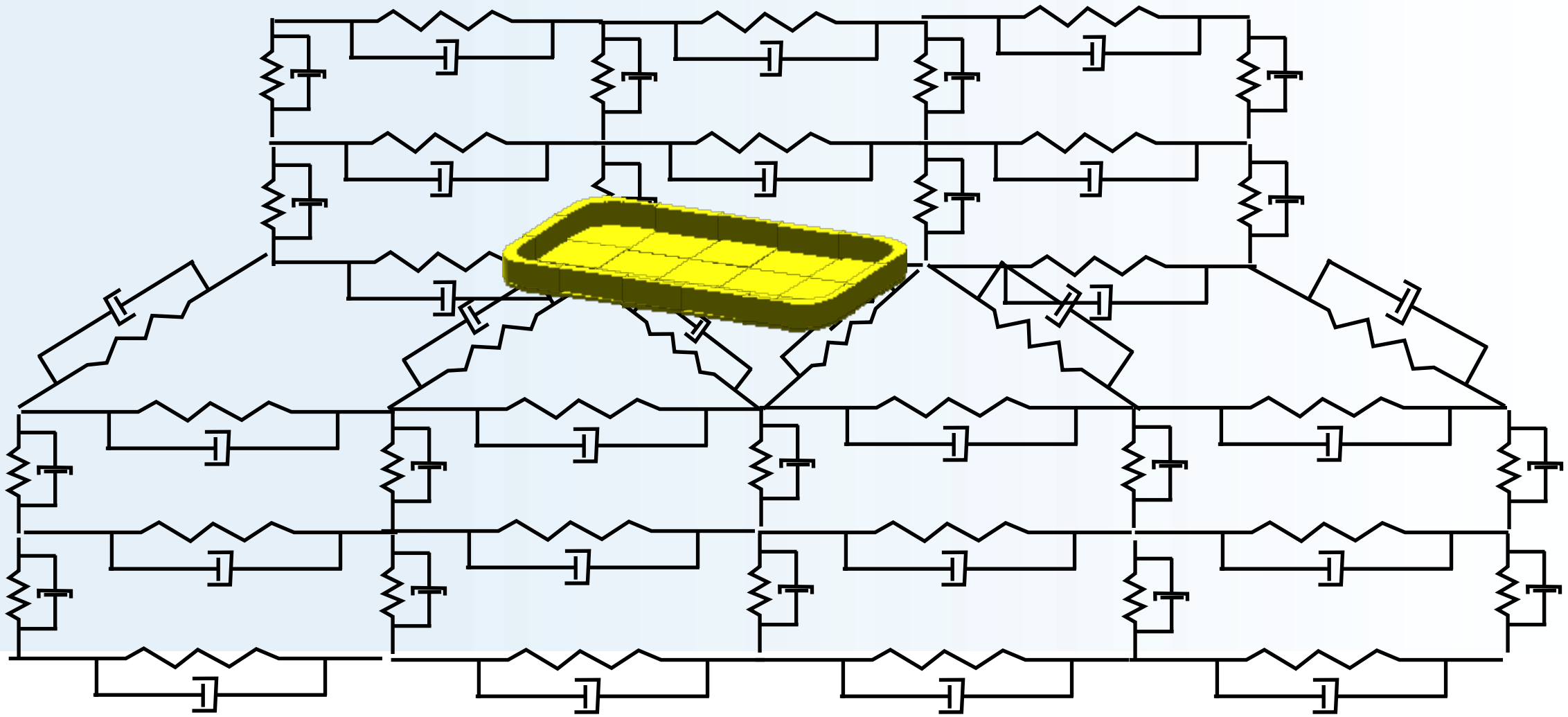
- Chassis Currents
  - Faults
  - Common mode currents
  - Lightning
- 2D / 3D transmission line



Mechanical

- Vibration / Shock
- Peak Stress
- Fatigue
- Kinematic Behavior
- Deformation

Lumped Mass Reduced Order Modeling



Coupling Elements as Tensors vs Constants

Stiffness Tensor

$$\begin{bmatrix} k_{xx23} & k_{xy23} & k_{xz23} \\ k_{yx23} & k_{yy23} & k_{yz23} \\ k_{zx23} & k_{zy23} & k_{zz23} \end{bmatrix}$$

Symmetry

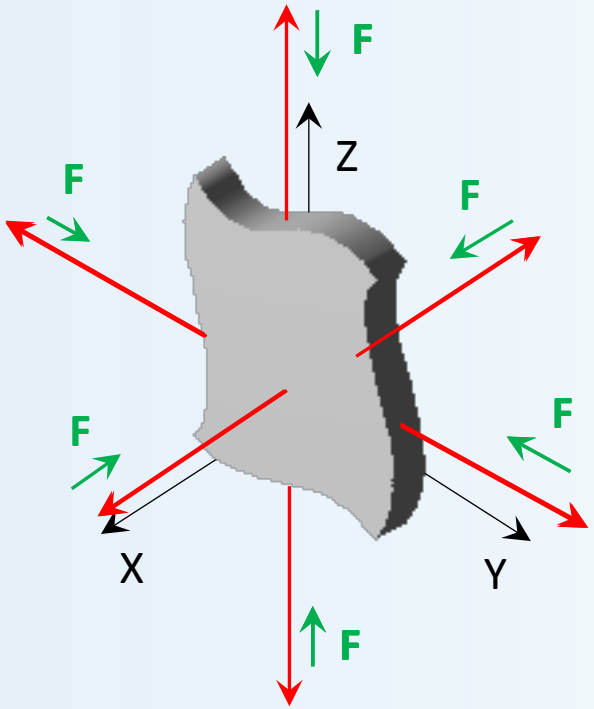
Damping Tensor

$$\begin{bmatrix} b_{xx23} & b_{xy23} & b_{xz23} \\ b_{yx23} & b_{yy23} & b_{yz23} \\ b_{zx23} & b_{zy23} & b_{zz23} \end{bmatrix}$$

Symmetry

Displacement / “Stretching”

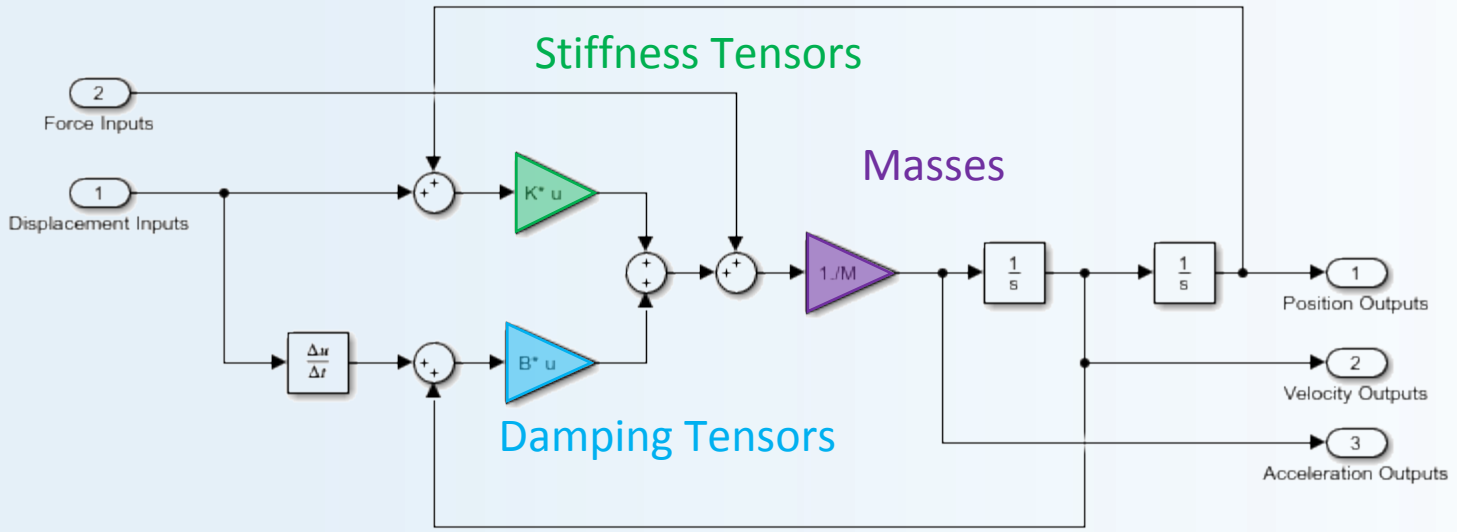
Force



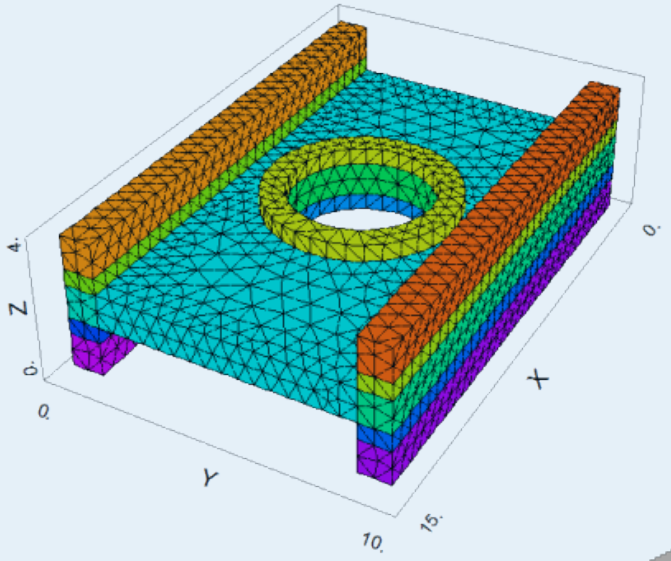
Stiffness Tensors in System Matrix

$$
\begin{bmatrix}
k_{xx11} & k_{xy11} & k_{xz11} & k_{xx12} & k_{xy12} & k_{xz12} & k_{xx13} & k_{xy13} & k_{xz13} & k_{xx14} & k_{xy14} & k_{xz14} \\
k_{yx11} & k_{yy11} & k_{yz11} & k_{yx12} & k_{yy12} & k_{yz12} & k_{yx13} & k_{yy13} & k_{yz13} & k_{yx14} & k_{yy14} & k_{yz14} \\
k_{zx11} & k_{zy11} & k_{zz11} & k_{zx12} & k_{zy12} & k_{zz12} & k_{zx13} & k_{zy13} & k_{zz13} & k_{zx14} & k_{zy14} & k_{zz14} \\
k_{xx21} & k_{xy21} & k_{xz21} & k_{xx22} & k_{xy22} & k_{xz22} & k_{xx23} & k_{xy23} & k_{xz23} & k_{xx24} & k_{xy24} & k_{xz24} \\
k_{yx21} & k_{yy21} & k_{yz21} & k_{yx22} & k_{yy22} & k_{yz22} & k_{yx23} & k_{yy23} & k_{yz23} & k_{yx24} & k_{yy24} & k_{yz24} \\
k_{zx21} & k_{zy21} & k_{zz21} & k_{zx22} & k_{zy22} & k_{zz22} & k_{zx23} & k_{zy23} & k_{zz23} & k_{zx24} & k_{zy24} & k_{zz24} \\
k_{xx31} & k_{xy31} & k_{xz31} & k_{xx32} & k_{xy32} & k_{xz32} & k_{xx33} & k_{xy33} & k_{xz33} & k_{xx34} & k_{xy34} & k_{xz34} \\
k_{yx31} & k_{yy31} & k_{yz31} & k_{yx32} & k_{yy32} & k_{yz32} & k_{yx33} & k_{yy33} & k_{yz33} & k_{yx34} & k_{yy34} & k_{yz34} \\
k_{zx31} & k_{zy31} & k_{zz31} & k_{zx32} & k_{zy32} & k_{zz32} & k_{zx33} & k_{zy33} & k_{zz33} & k_{zx34} & k_{zy34} & k_{zz34} \\
k_{xx41} & k_{xy41} & k_{xz41} & k_{xx42} & k_{xy42} & k_{xz42} & k_{xx43} & k_{xy43} & k_{xz43} & k_{xx44} & k_{xy44} & k_{xz44} \\
k_{yx41} & k_{yy41} & k_{yz41} & k_{yx42} & k_{yy42} & k_{yz42} & k_{yx43} & k_{yy43} & k_{yz43} & k_{yx44} & k_{yy44} & k_{yz44} \\
k_{zx41} & k_{zy41} & k_{zz41} & k_{zx42} & k_{zy42} & k_{zz42} & k_{zx43} & k_{zy43} & k_{zz43} & k_{zx44} & k_{zy44} & k_{zz44}
\end{bmatrix}
$$

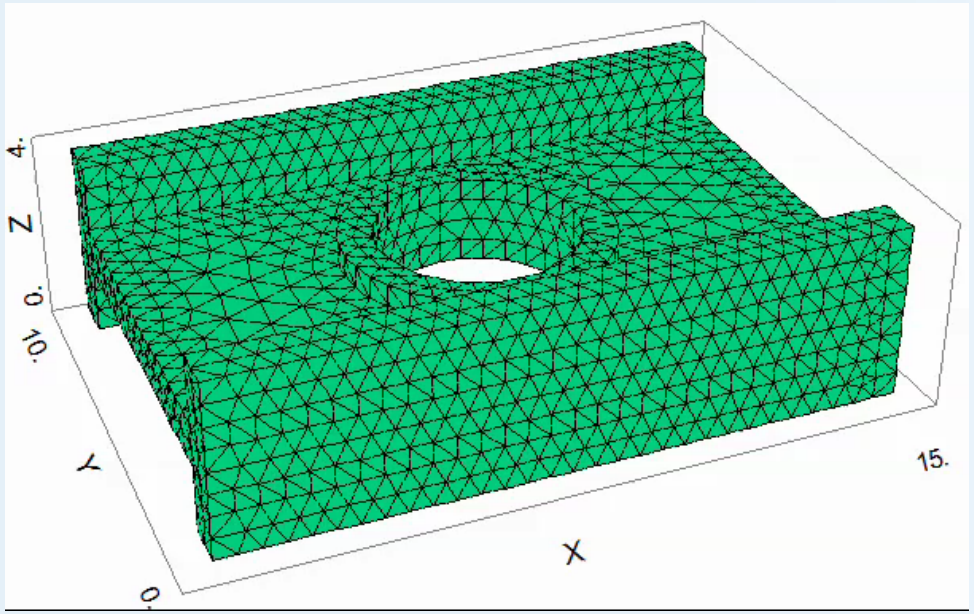
Modeling Mechanical Vibrations and Thermal Conduction in Simulink



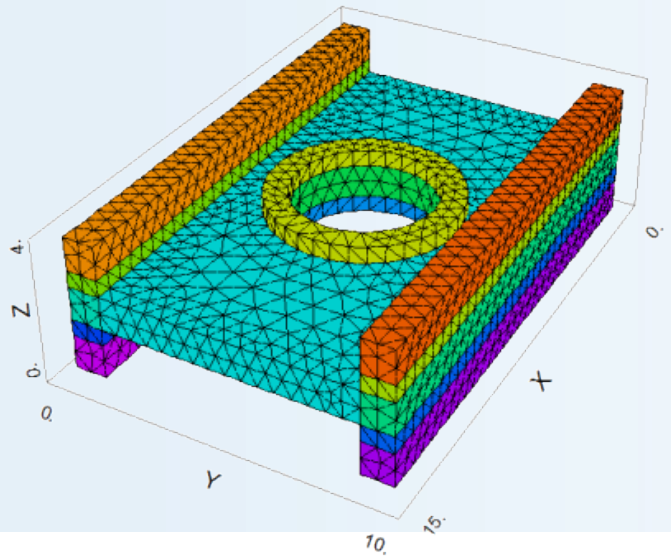
Vibration Example – Shell



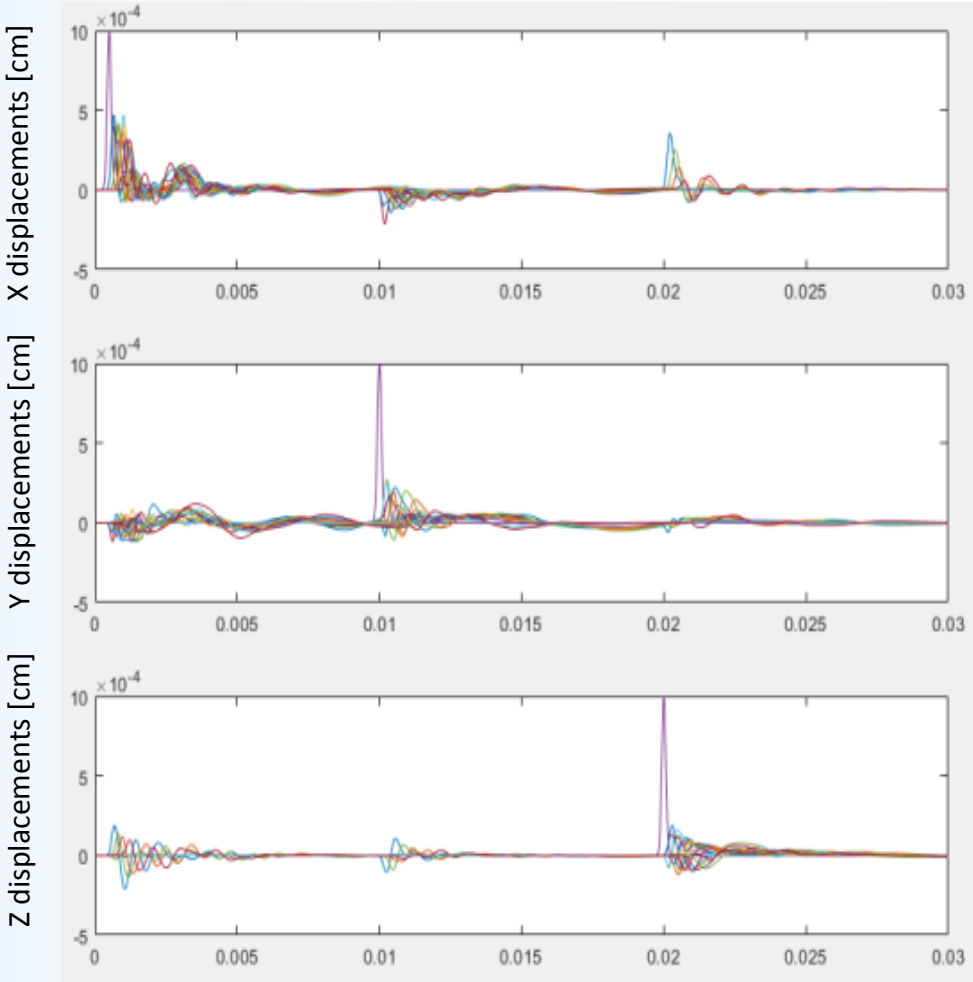
Vibration Example – Beam



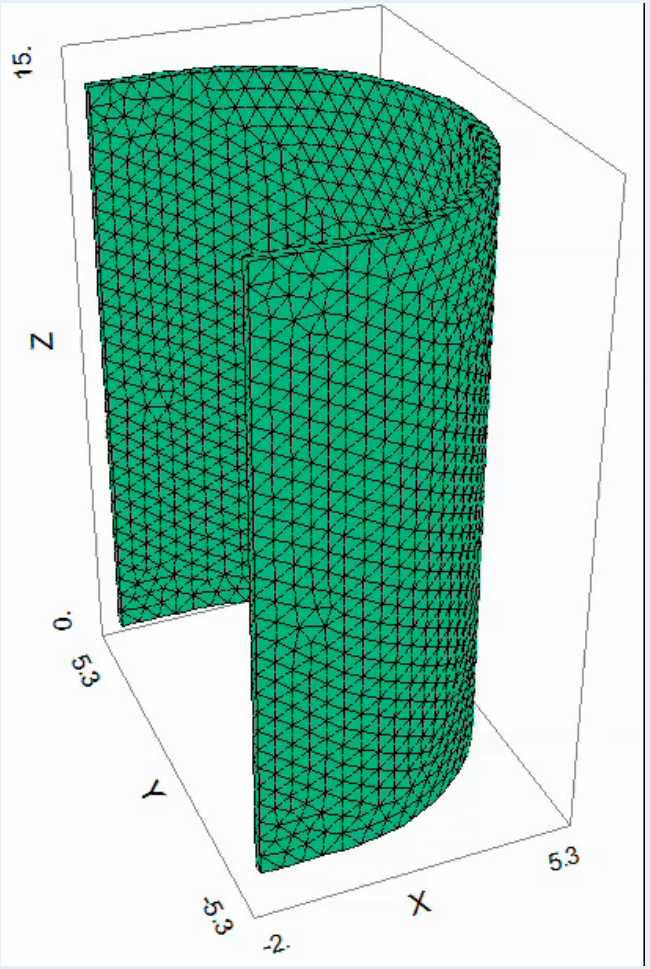
[Click on Video]



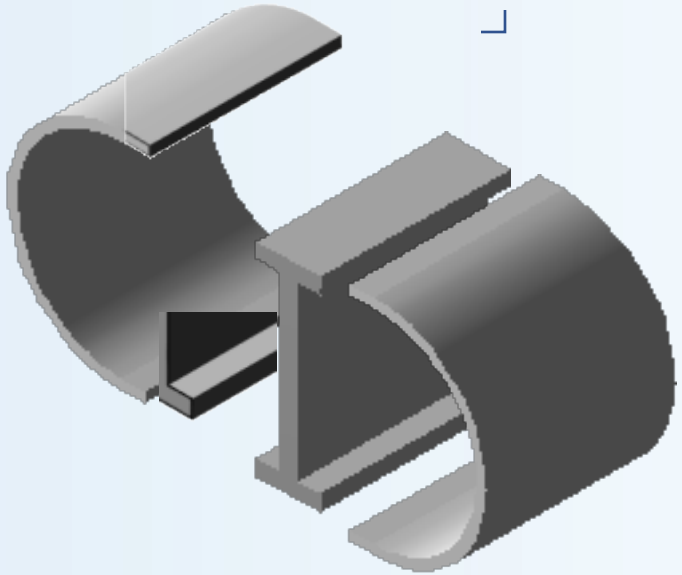
Displacements



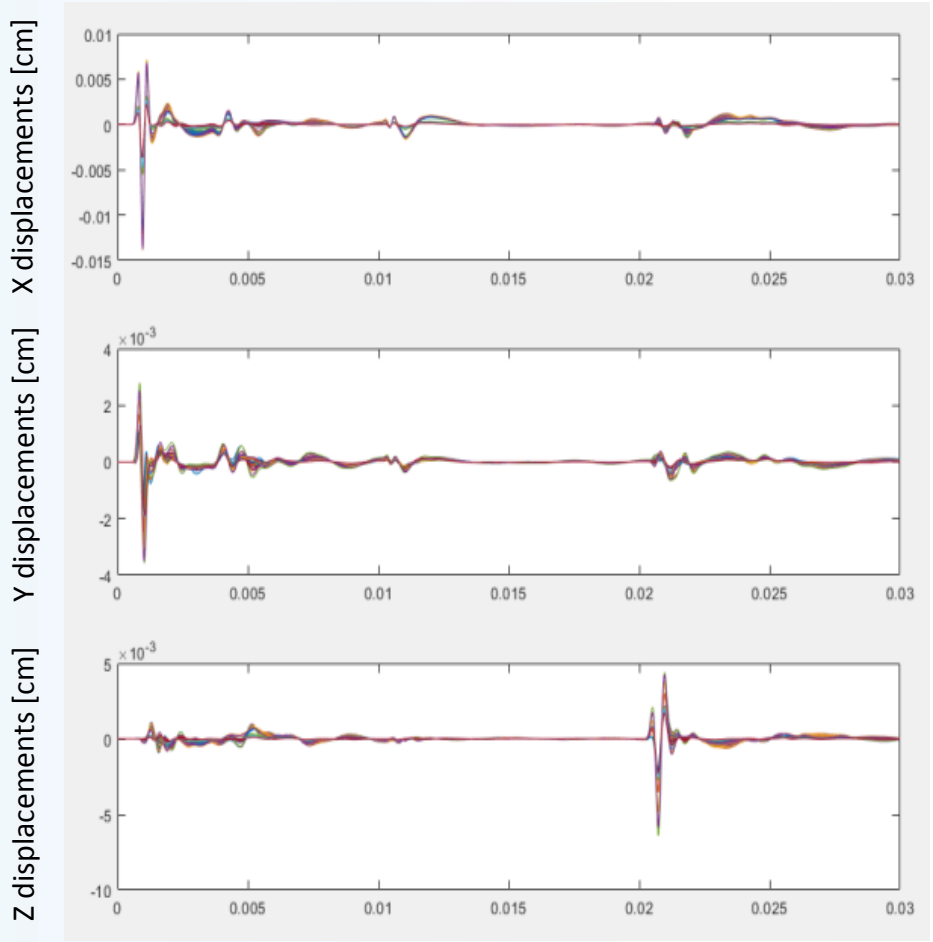
Vibration Example – Shell



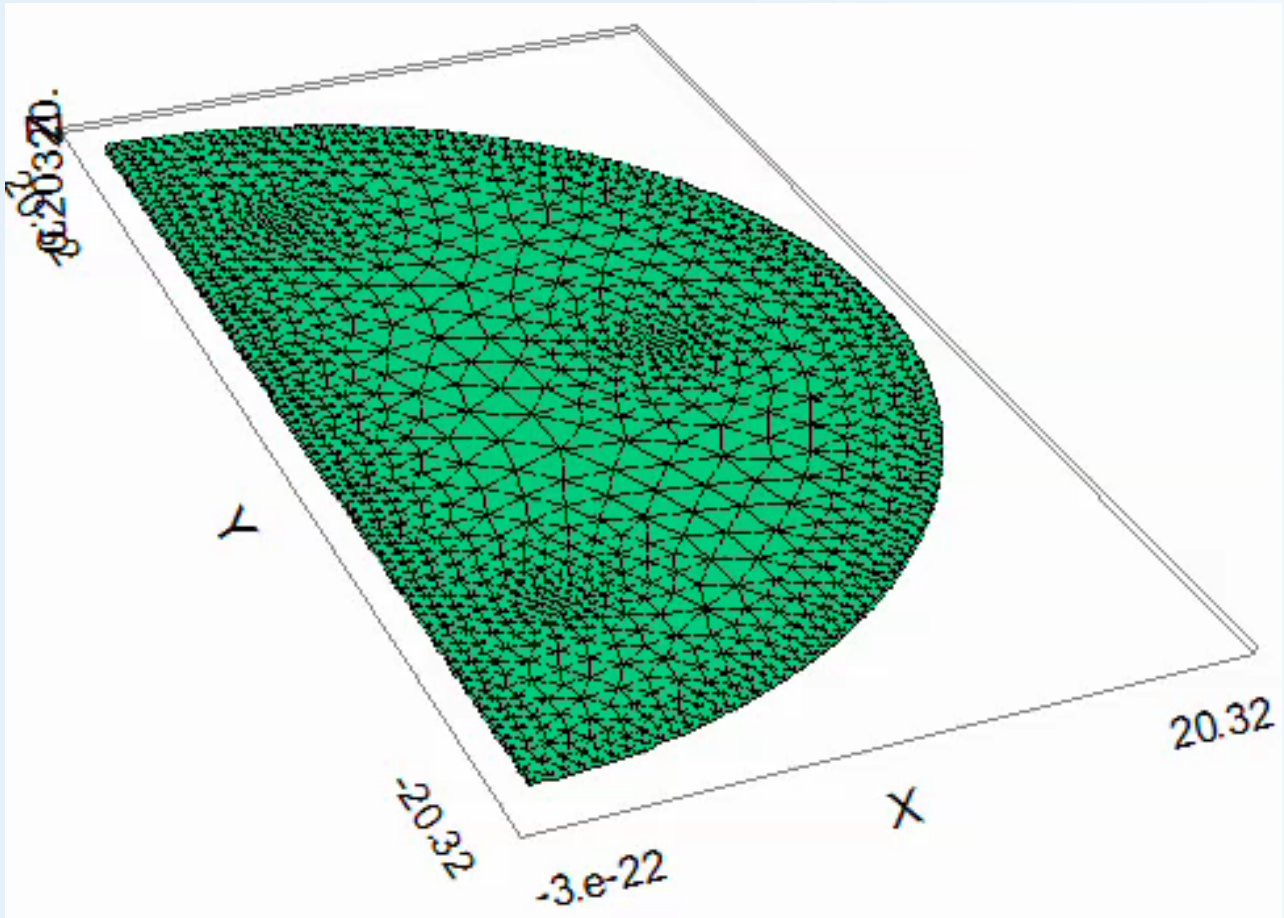
[Click on Video]



Displacements

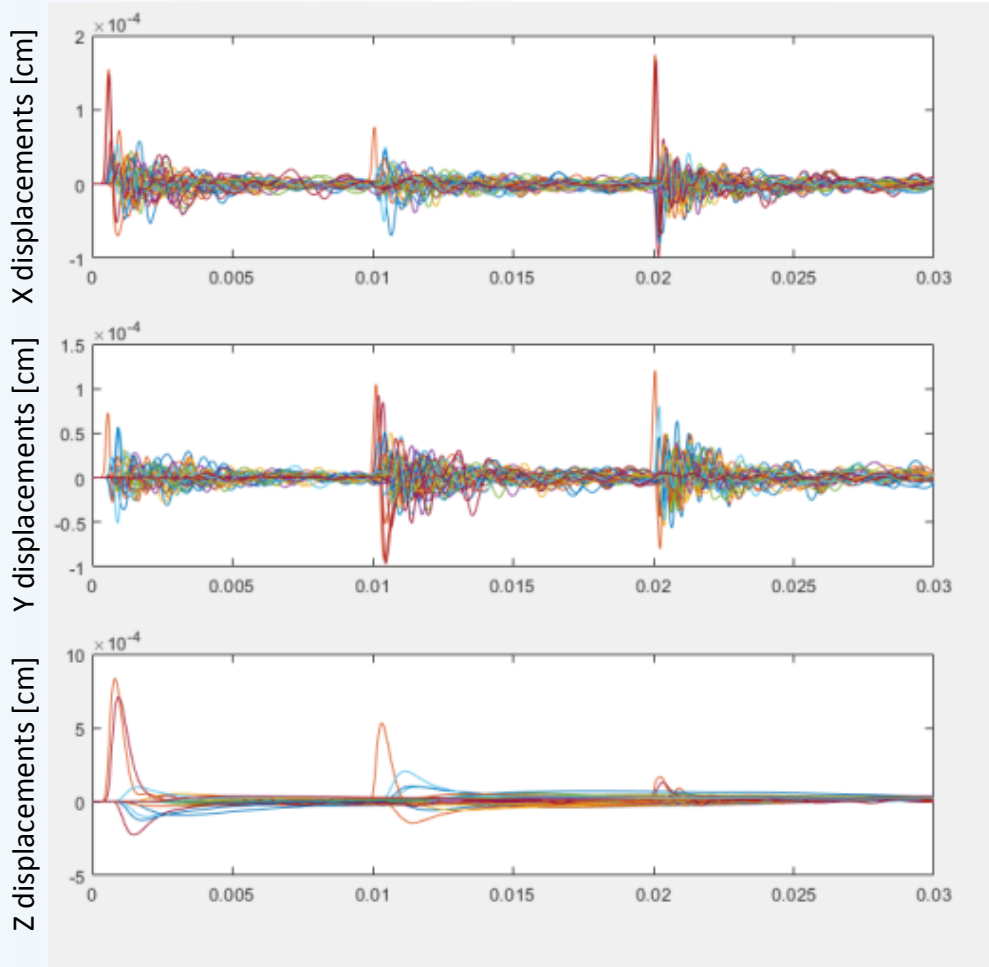


Vibration Example – Circuit Board



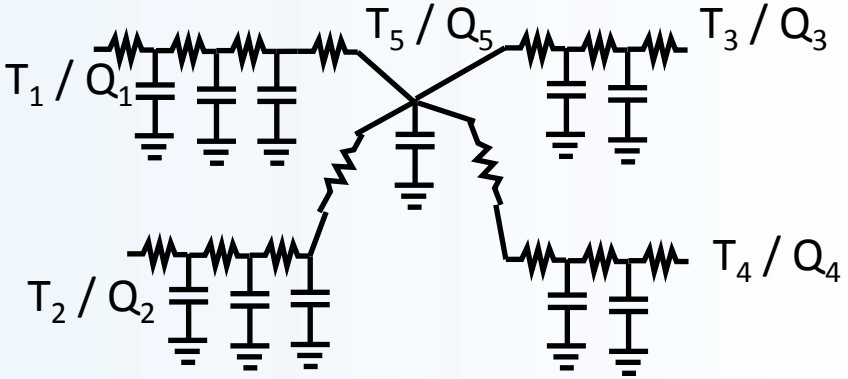
[Click on Video]

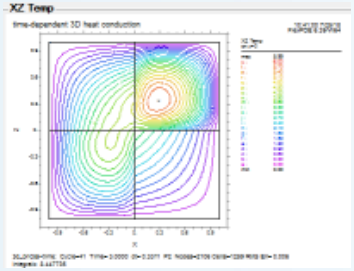
Displacements

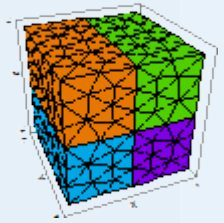


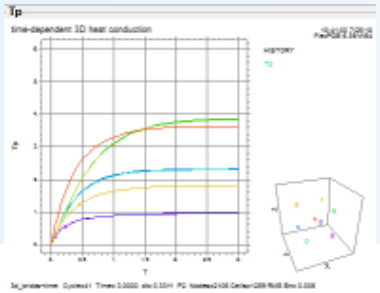
Thermal Modeling

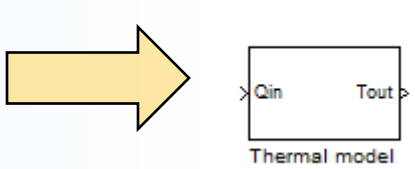
- Conduction
  - Thermal Resistance
  - Thermal Capacitance
- Convection
  - Free
  - Forced
- Radiation







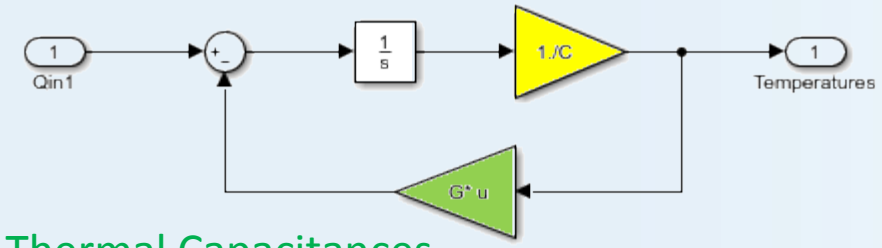




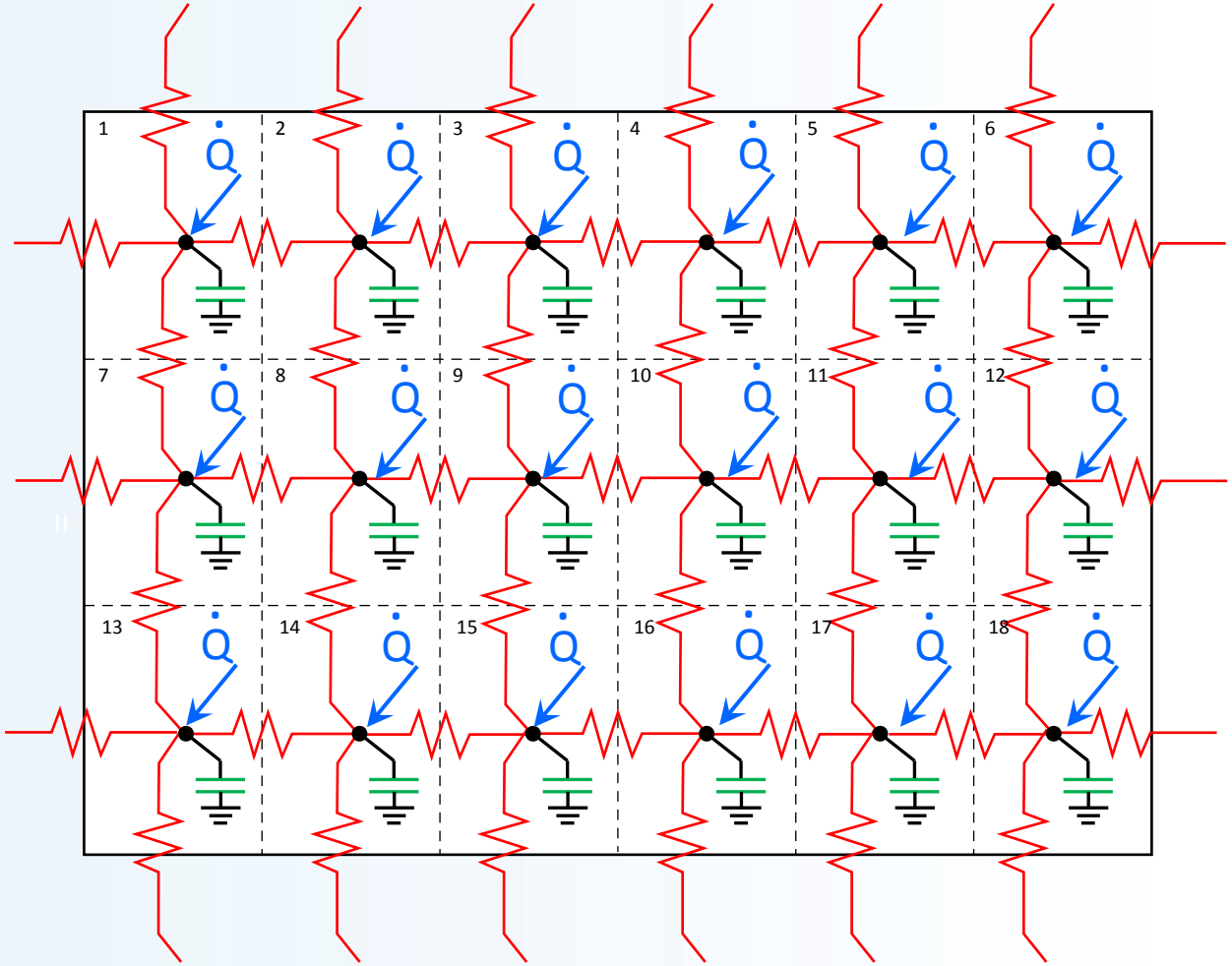
Thermal Modeling - Conduction

$$\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \\ Q_5 \\ Q_6 \\ Q_7 \\ Q_8 \\ \cdot \\ \cdot \\ \cdot \\ Q_{18} \end{bmatrix} - \begin{bmatrix} G \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \\ \cdot \\ \cdot \\ \cdot \\ T_{18} \end{bmatrix} = S \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \\ C_7 \\ C_8 \\ \cdot \\ \cdot \\ \cdot \\ C_{18} \end{bmatrix} .* \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \\ \cdot \\ \cdot \\ \cdot \\ T_{18} \end{bmatrix}$$

Thermal Capacitances



Thermal Capacitances



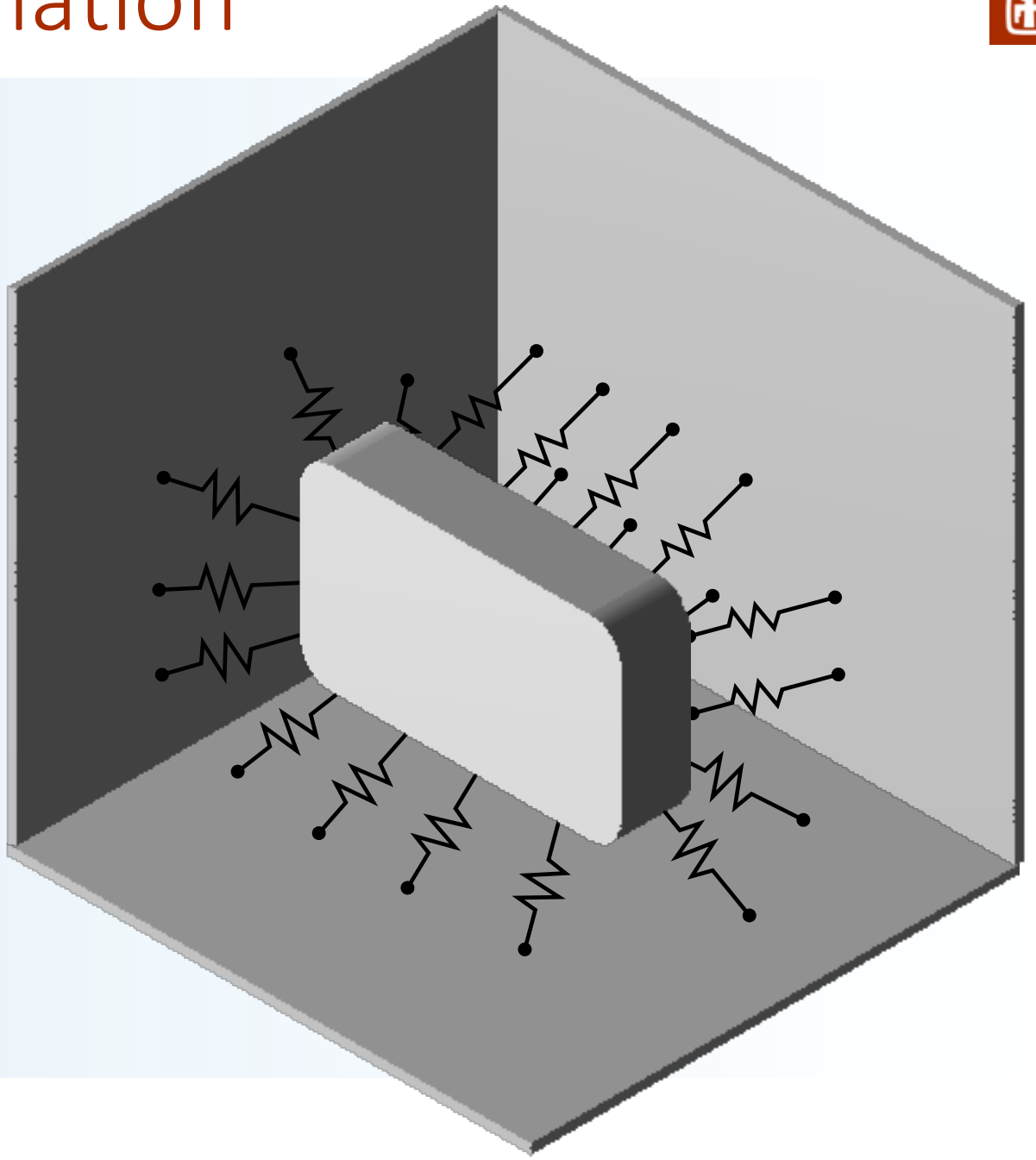
Thermal Modeling – Conduction Matrix

$$[G] = \begin{bmatrix}
-\Sigma row & -1/R_{12} & 0 & 0 & 0 & 0 & -1/R_{17} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1/R_{12} & -\Sigma row & -1/R_{23} & 0 & 0 & 0 & 0 & -1/R_{28} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1/R_{23} & -\Sigma row & -1/R_{34} & 0 & 0 & 0 & 0 & -1/R_{39} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1/R_{34} & -\Sigma row & -1/R_{45} & 0 & 0 & 0 & 0 & -1/R_{410} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1/R_{45} & -\Sigma row & -1/R_{56} & 0 & 0 & 0 & 0 & -1/R_{511} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1/R_{56} & -\Sigma row & 0 & 0 & 0 & 0 & 0 & -1/R_{612} & 0 & 0 & 0 & 0 & 0 & 0 \\
-1/R_{17} & 0 & 0 & 0 & 0 & -1/R_{67} & -\Sigma row & -1/R_{67} & 0 & 0 & 0 & 0 & -1/R_{713} & 0 & 0 & 0 & 0 & 0 \\
0 & -1/R_{28} & 0 & 0 & 0 & 0 & -1/R_{78} & -\Sigma row & -1/R_{89} & 0 & 0 & 0 & 0 & -1/R_{814} & 0 & 0 & 0 & 0 \\
0 & 0 & -1/R_{39} & 0 & 0 & 0 & 0 & -1/R_{89} & -\Sigma row & -1/R_{910} & 0 & 0 & 0 & 0 & -1/R_{915} & 0 & 0 & 0 \\
0 & 0 & 0 & -1/R_{410} & 0 & 0 & 0 & 0 & -1/R_{910} & -\Sigma row & -1/R_{1011} & 0 & 0 & 0 & 0 & -1/R_{1016} & 0 & 0 \\
0 & 0 & 0 & 0 & -1/R_{511} & 0 & 0 & 0 & 0 & -1/R_{910} & -\Sigma row & -1/R_{1011} & 0 & 0 & 0 & 0 & -1/R_{1117} & 0 \\
0 & 0 & 0 & 0 & 0 & -1/R_{612} & 0 & 0 & 0 & 0 & -1/R_{1011} & -\Sigma row & -1/R_{1112} & 0 & 0 & 0 & 0 & -1/R_{1218} \\
0 & 0 & 0 & 0 & 0 & 0 & -1/R_{713} & 0 & 0 & 0 & 0 & -1/R_{1112} & -\Sigma row & -1/R_{1213} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/R_{814} & 0 & 0 & 0 & 0 & -1/R_{1213} & -\Sigma row & -1/R_{1314} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/R_{915} & 0 & 0 & 0 & 0 & -1/R_{1314} & -\Sigma row & -1/R_{1415} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/R_{1016} & 0 & 0 & 0 & 0 & -1/R_{1415} & -\Sigma row & -1/R_{1516} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/R_{1117} & 0 & 0 & 0 & 0 & -1/R_{1516} & -\Sigma row & -1/R_{1617} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/R_{1218} & 0 & 0 & 0 & 0 & -1/R_{1617} & -\Sigma row
\end{bmatrix}$$

Thermal Modeling - Radiation

$$\frac{q}{A} = \varepsilon k_b (T_1^4 - T_2^4) = \frac{\Delta T}{R}$$

$$R = \frac{(T_1 - T_2)}{\varepsilon k_b (T_1^4 - T_2^4)}$$



Electro-Mechanical

- Motors / Actuators
- Electrical Connectors ← Thermal ← shock/vibe
- Pyro ← Thermal ← Pressure Waves

Fluids

Gasses / Pneumatics
Pressure Waves / Pyrotechnics

Electro-Magnetic Fields

Radiated EMI (Power Converters)
Radar
Other..

Backup Slides

Extraction of Parameters

Four Element Example in 1D

$\underline{M_1}$

$(k_{01}+sb_{01})(x_0 - x_1) + (k_{21}+sb_{21})(x_2 - x_1) + (k_{31}+sb_{31})(x_3 - x_1) + (k_{41}+sb_{41})(x_4 - x_1) = M_1 s^2 x_1$

$\underline{M_2}$

$(k_{02}+sb_{02})(x_0 - x_2) + (k_{21}+sb_{21})(x_1 - x_2) + (k_{32}+sb_{32})(x_3 - x_2) + (k_{42}+sb_{42})(x_4 - x_2) = M_2 s^2 x_2$

$\underline{M_3}$

$(k_{03}+sb_{03})(x_0 - x_3) + (k_{13}+sb_{13})(x_1 - x_3) + (k_{23}+sb_{23})(x_2 - x_3) + (k_{43}+sb_{43})(x_4 - x_3) = M_3 s^2 x_3$

$\underline{M_4}$

$(k_{04}+sb_{04})(x_0 - x_4) + (k_{14}+sb_{14})(x_1 - x_4) + (k_{24}+sb_{24})(x_2 - x_4) + (k_{34}+sb_{34})(x_3 - x_4) = M_4 s^2 x_4$

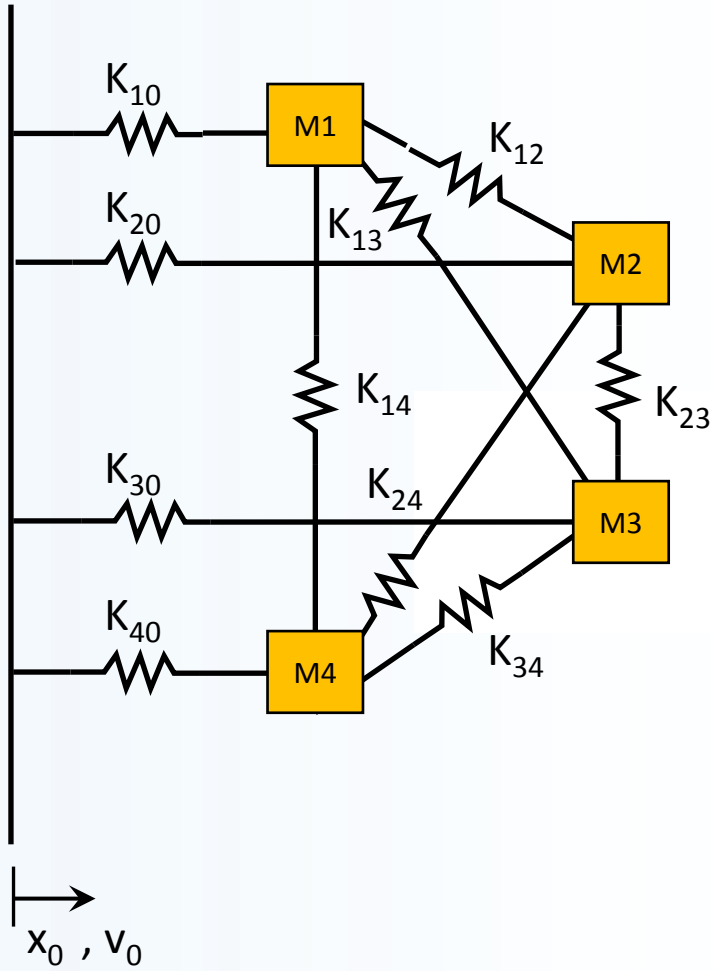
Multivariable Regression

$\underline{M_1}$

$$\frac{k_{01}}{M_1}(x_0 - x_1) + \frac{b_{01}}{M_1}(v_0 - v_1) + \frac{k_{21}}{M_1}(x_2 - x_1) + \frac{b_{21}}{M_1}(v_2 - v_1) + \frac{k_{31}}{M_1}(x_3 - x_1) + \frac{b_{31}}{M_1}(v_3 - v_1) + \frac{k_{41}}{M_1}(x_4 - x_1) + \frac{b_{41}}{M_1}(v_4 - v_1) = a_1$$

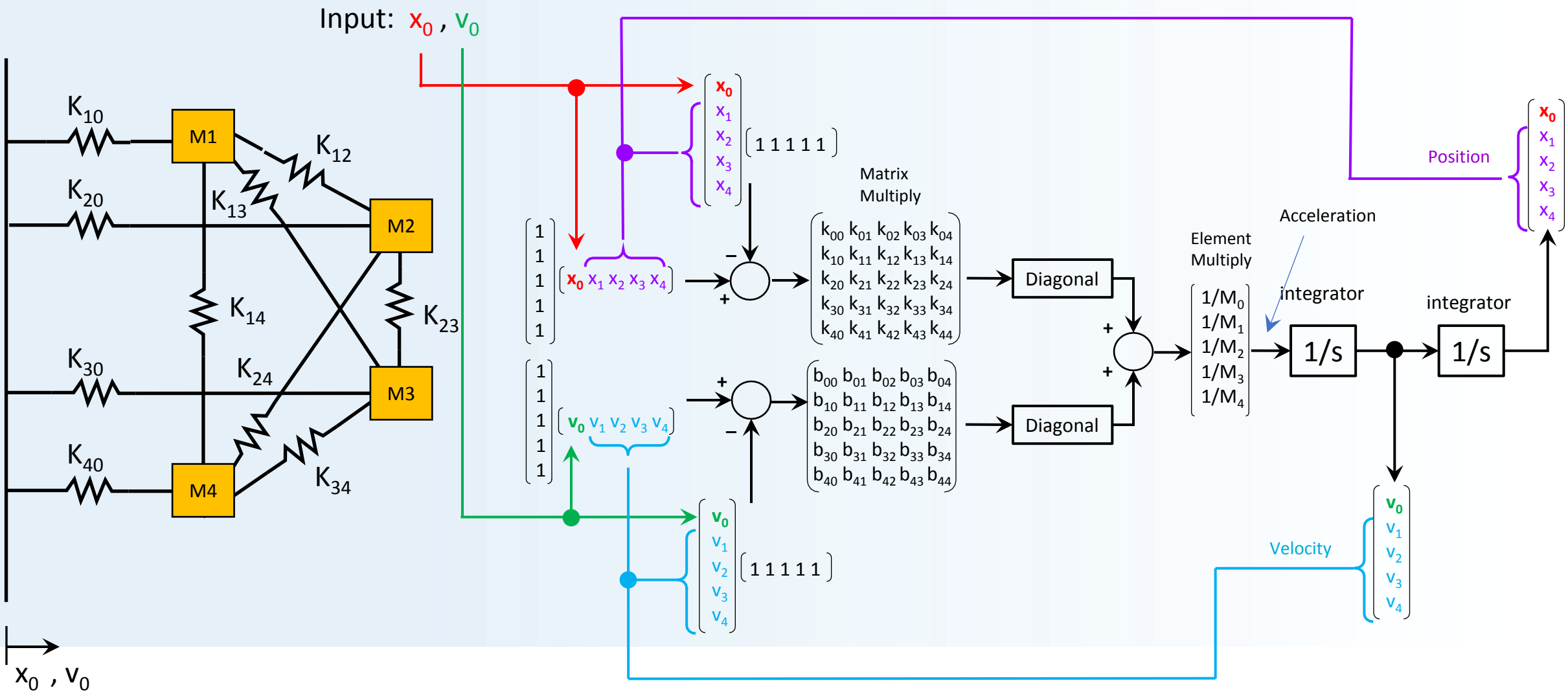
Known

Unknown

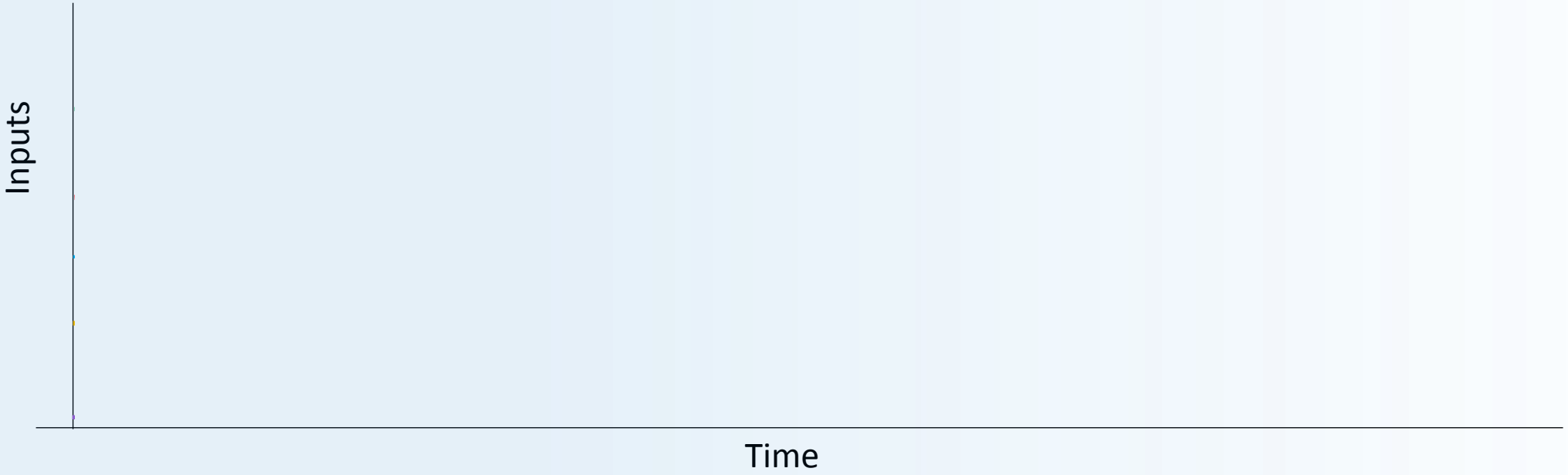


Solve for Unknowns → Extract Stiffness and Damping tensor components

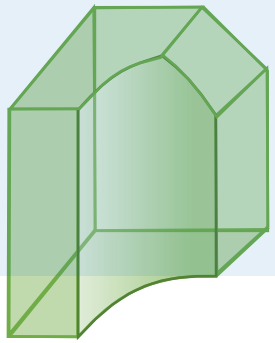
4 Element System in 1D



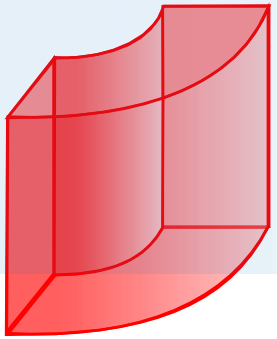
Full System Model Simulation Indicates when Model Components go out of spec



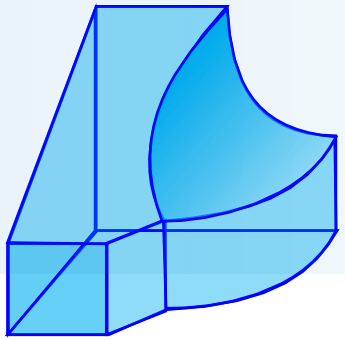
Component 1



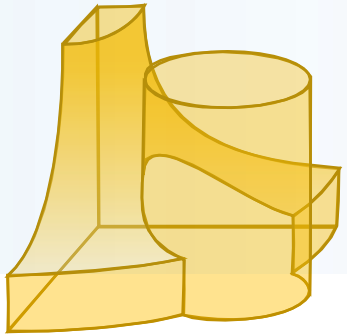
Component 2



Component 3



Component 4



Component 5