SAND2018-13953PE

Tip-to-Tail System Modeling Using Reduced Order Modeling

PRESENTED BY

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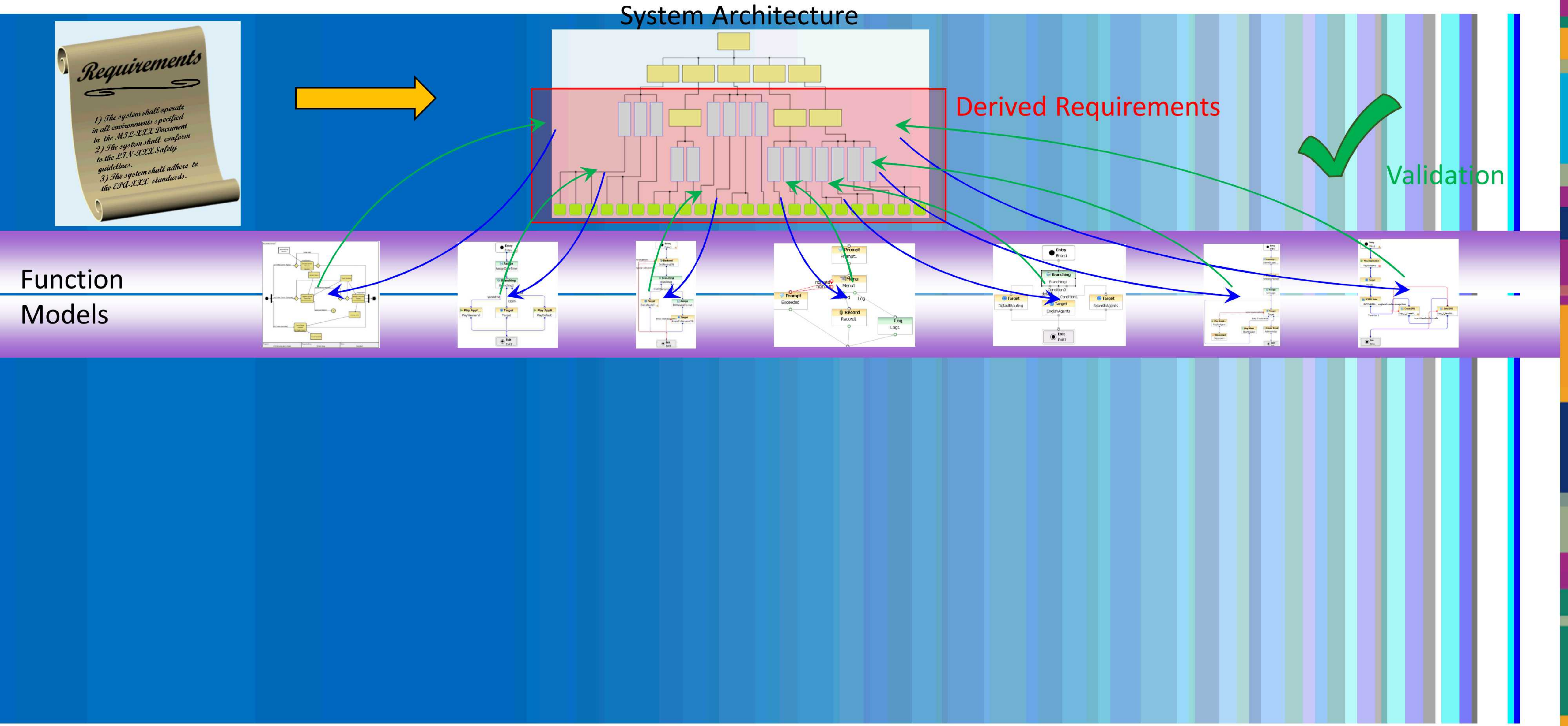
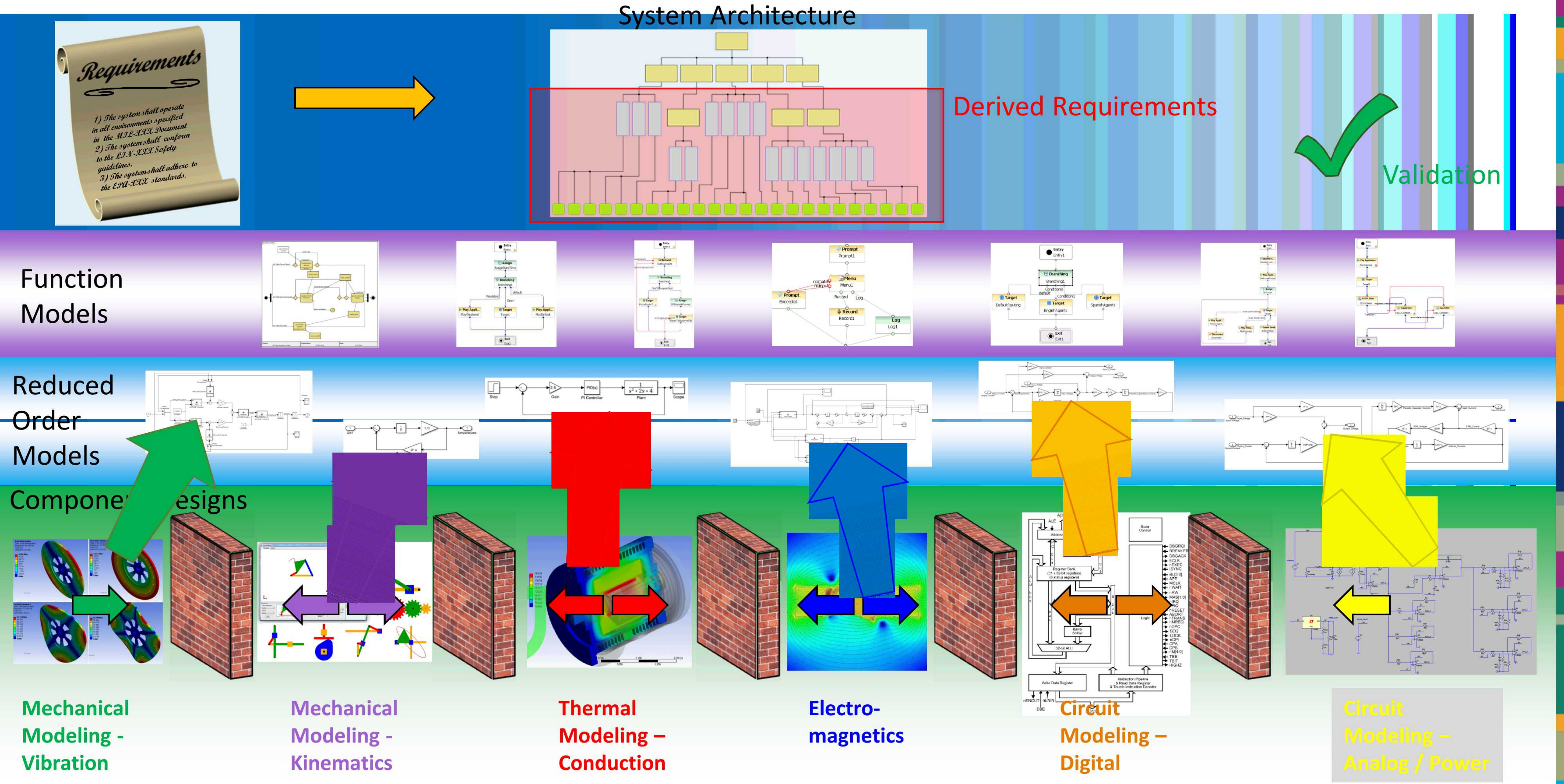
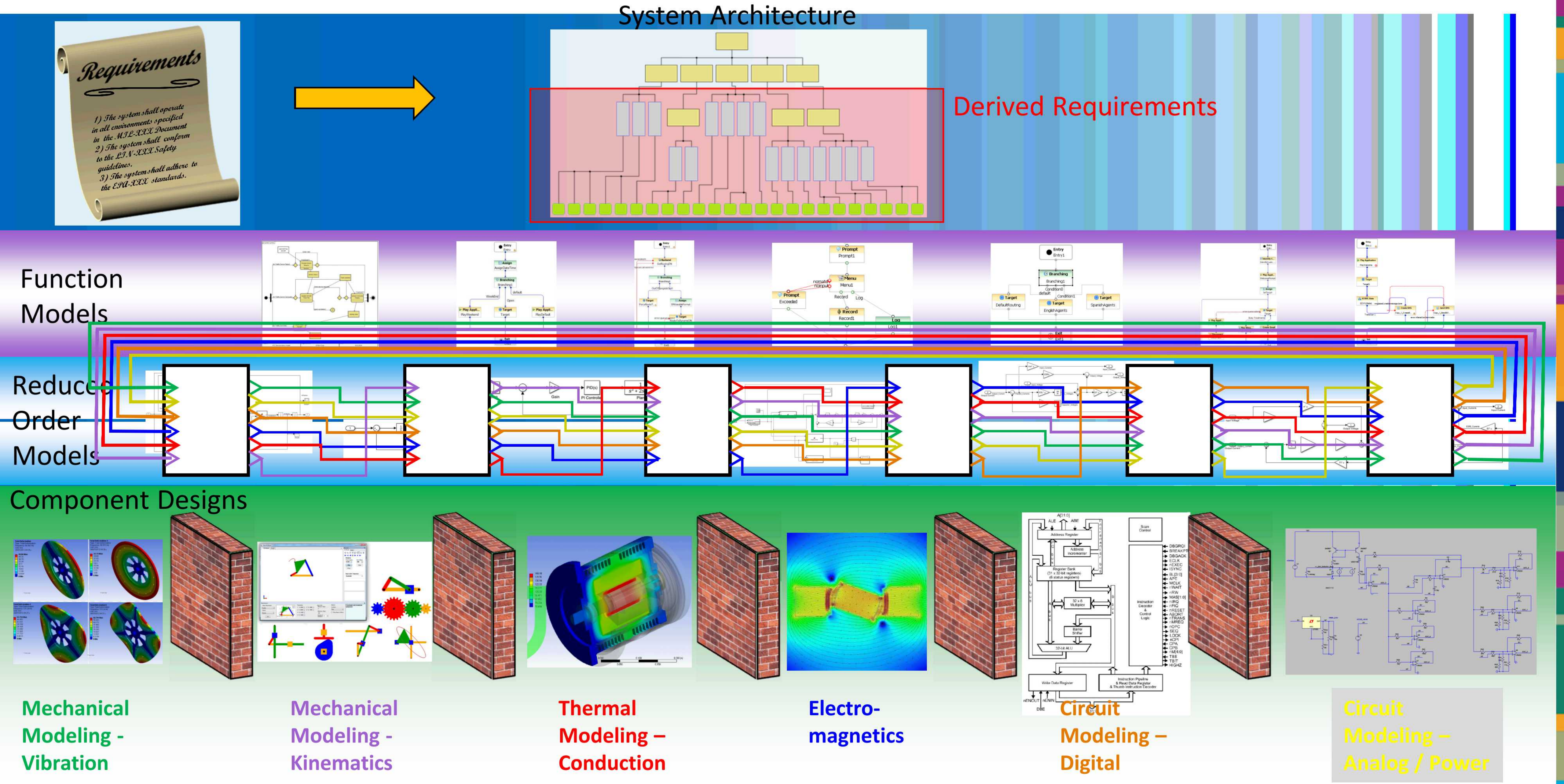
The Role of MBSE and Reduced Order Modeling



The Role of MBSE and Reduced Order Modeling

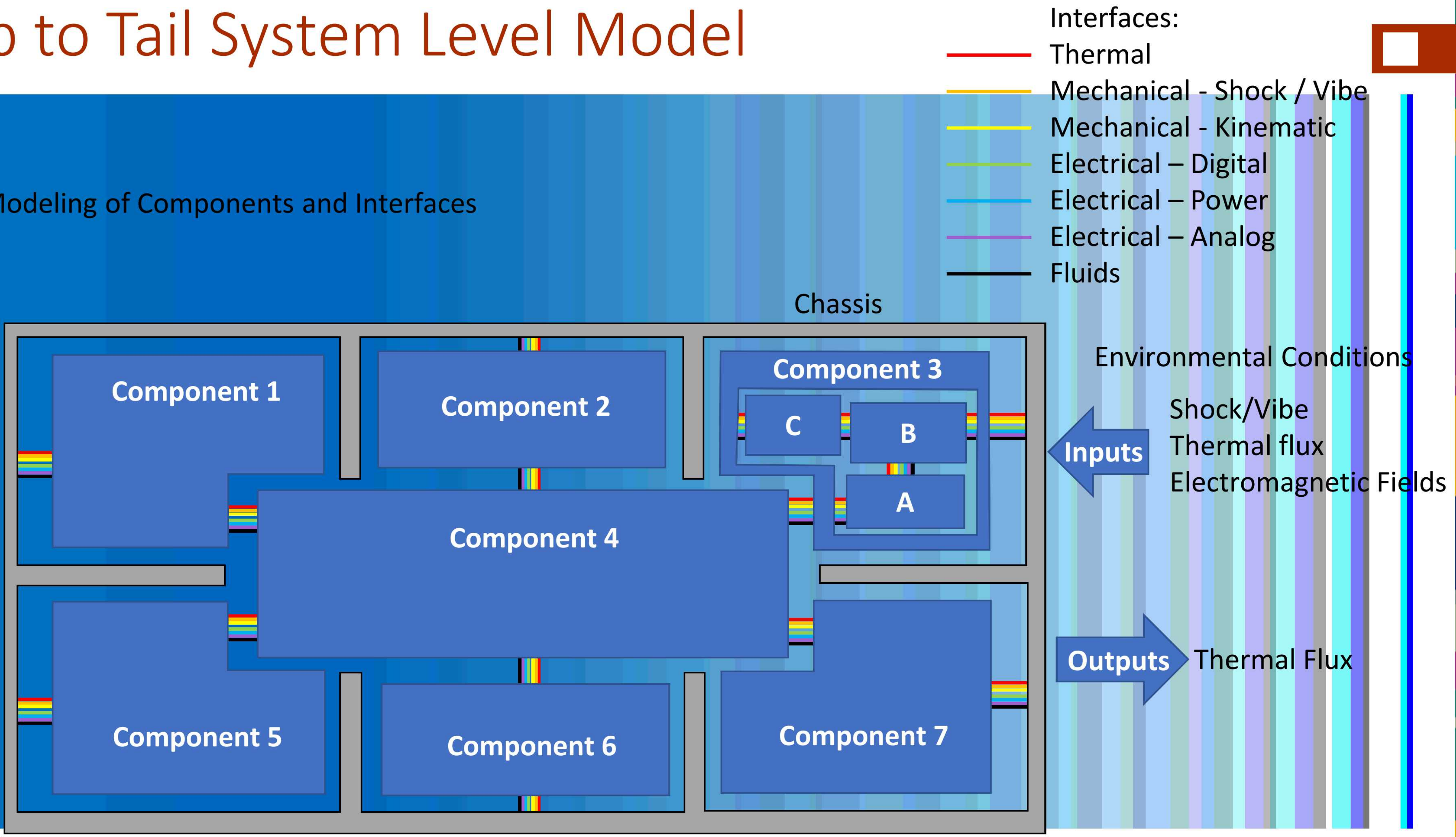


The Role of MBSE and Reduced Order Modeling

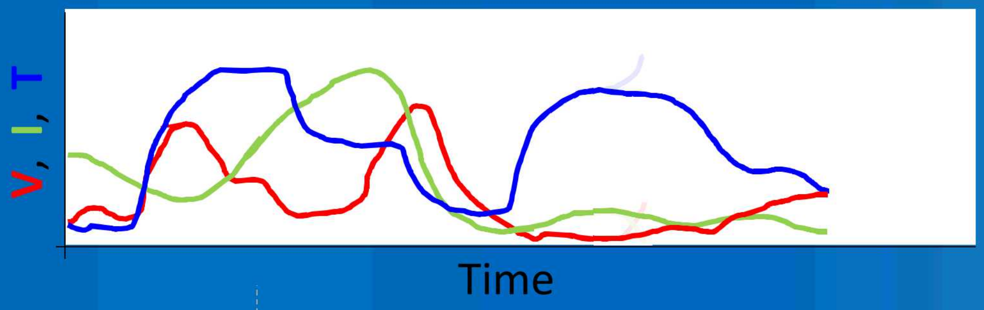


Tip to Tail System Level Model

Modeling of Components and Interfaces



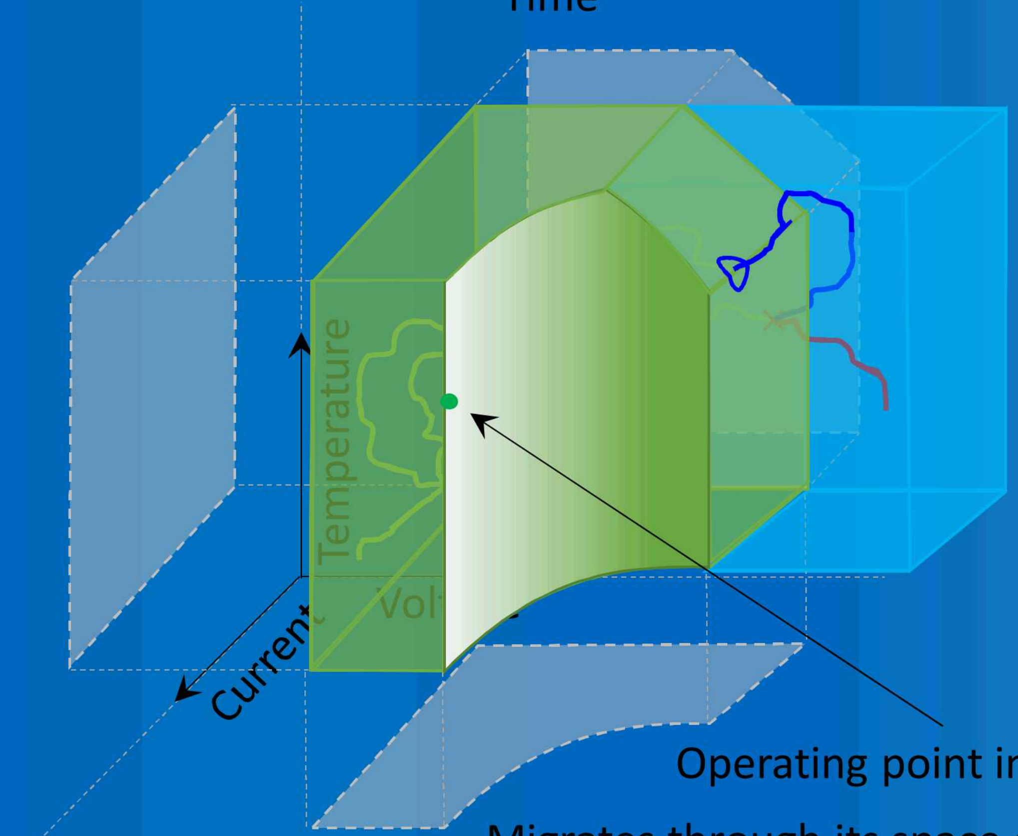
Physics Variable Trajectories



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

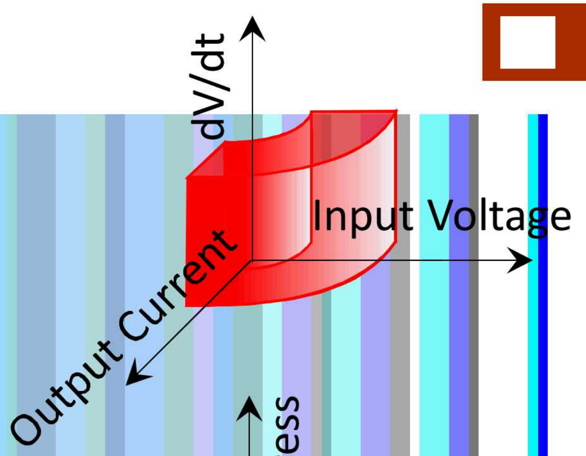
If external conditions force the modeled component beyond its limits of accuracy,

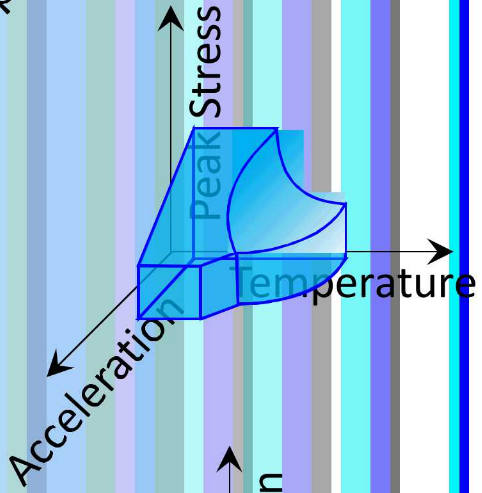
A piece-wise extended model can be made to extend the accuracy of the component’s model, if necessary.

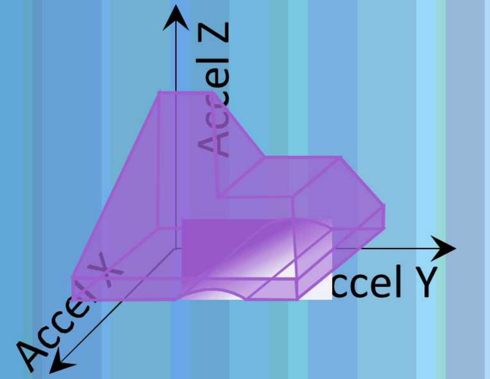


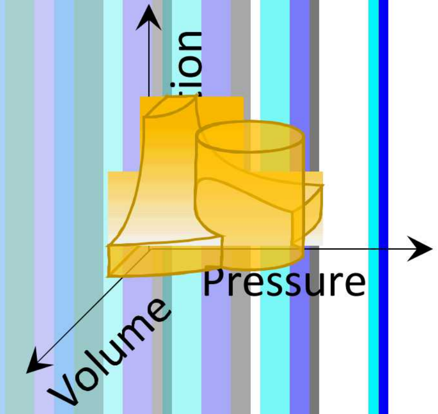
Operating point in simulation space

Migrates through its space during a simulation

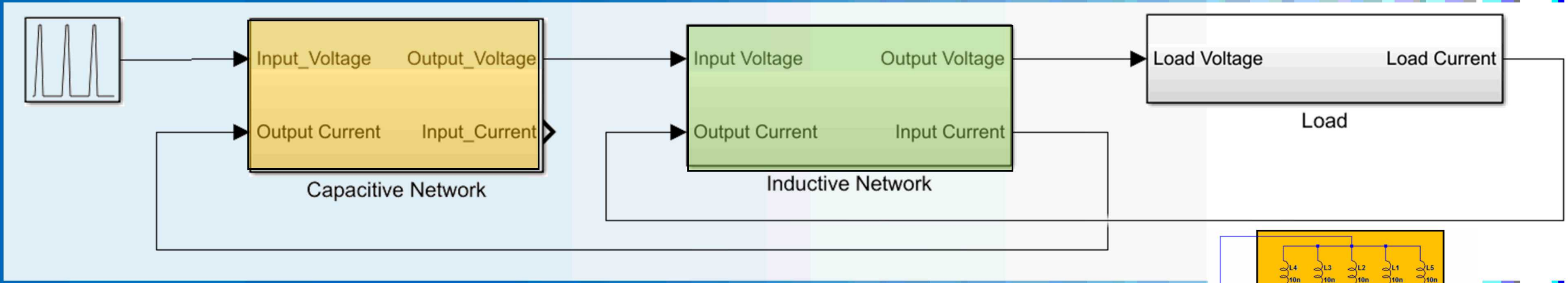


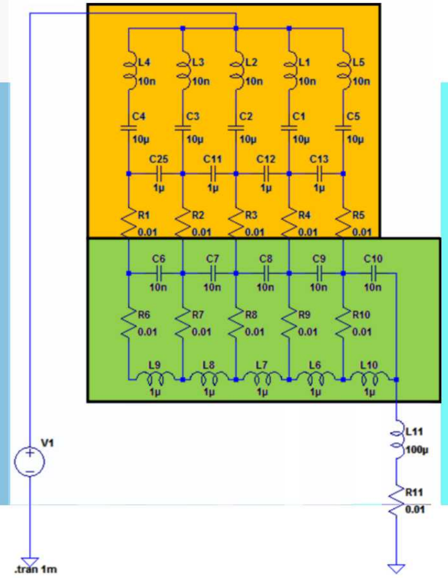




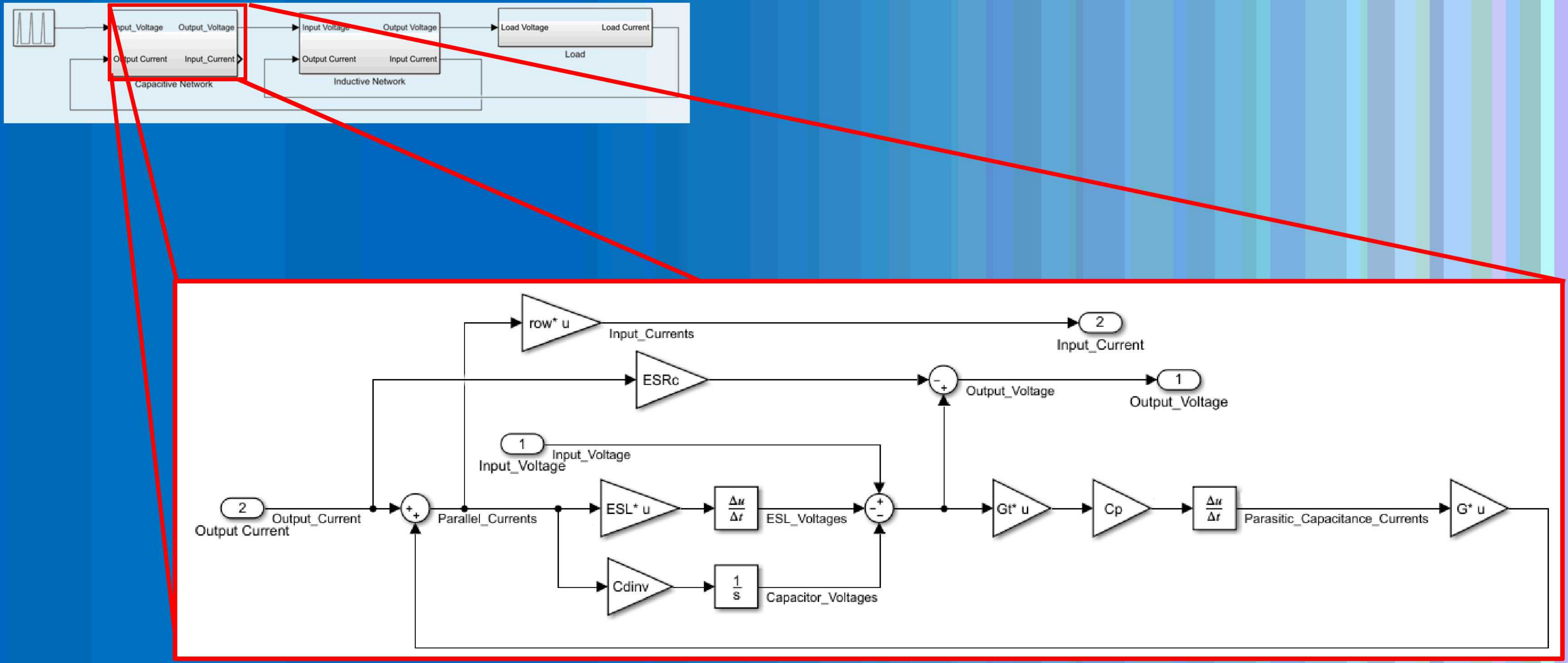


Connecting Passive Electrical Components



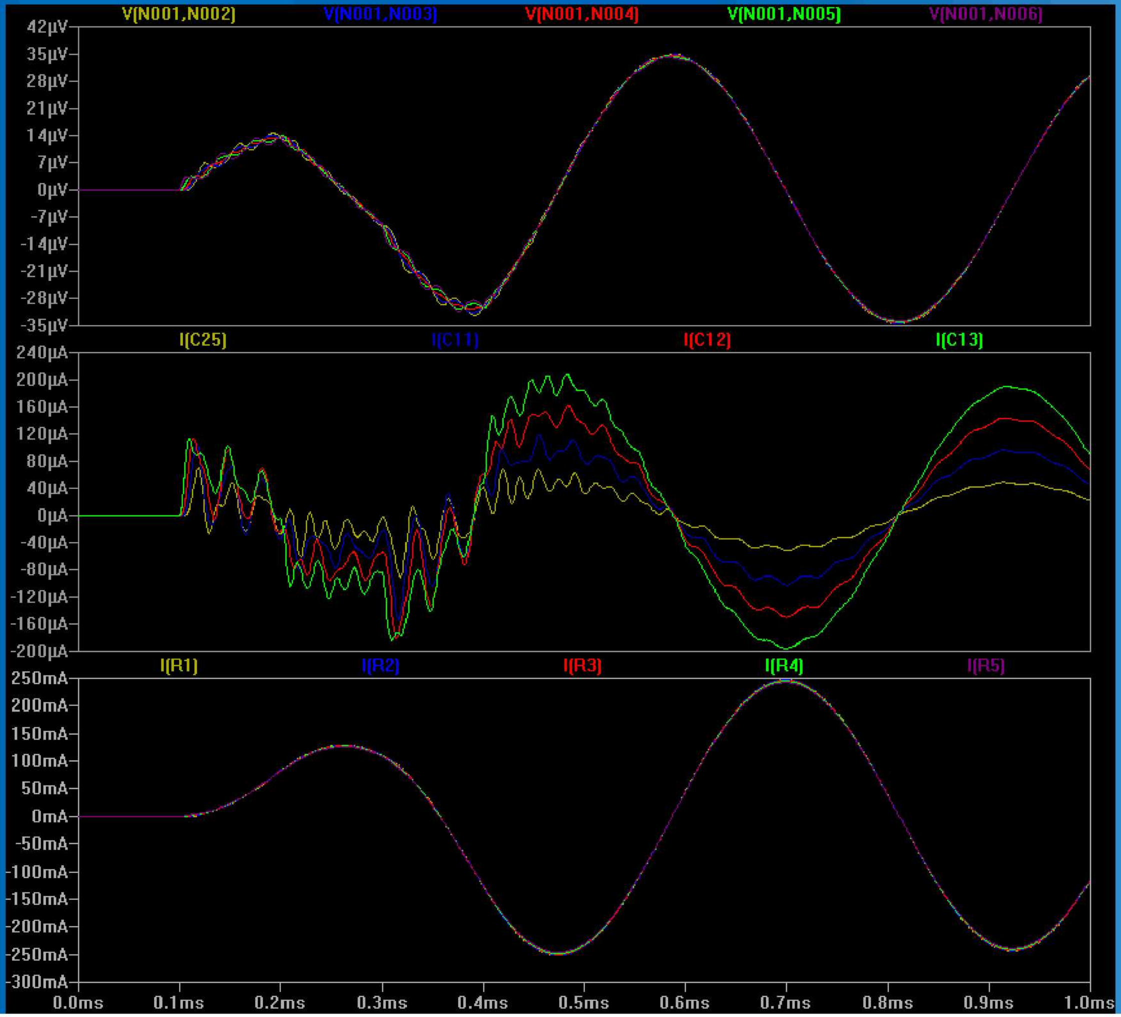


Electrical Modeling

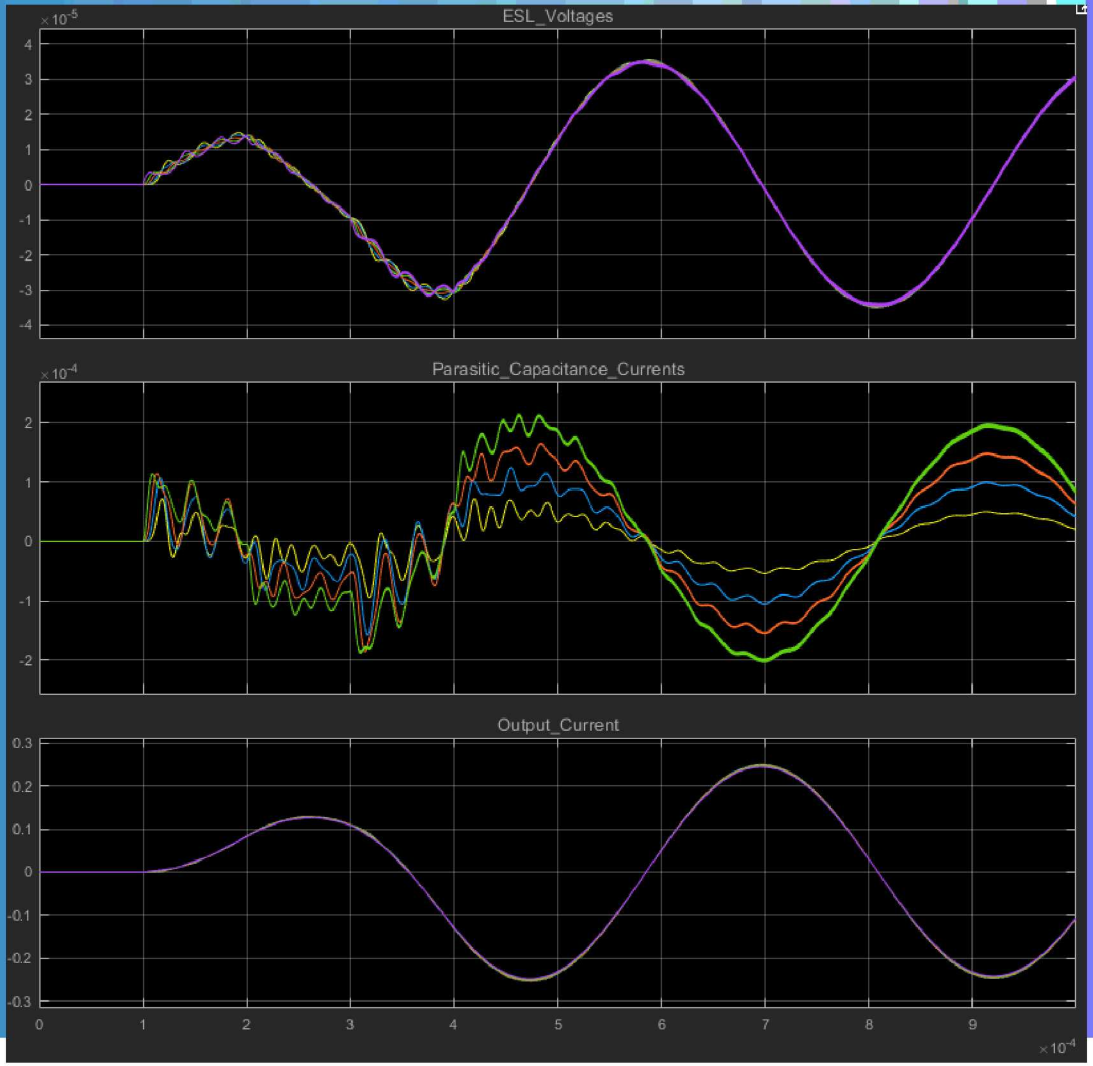


Electrical Modeling

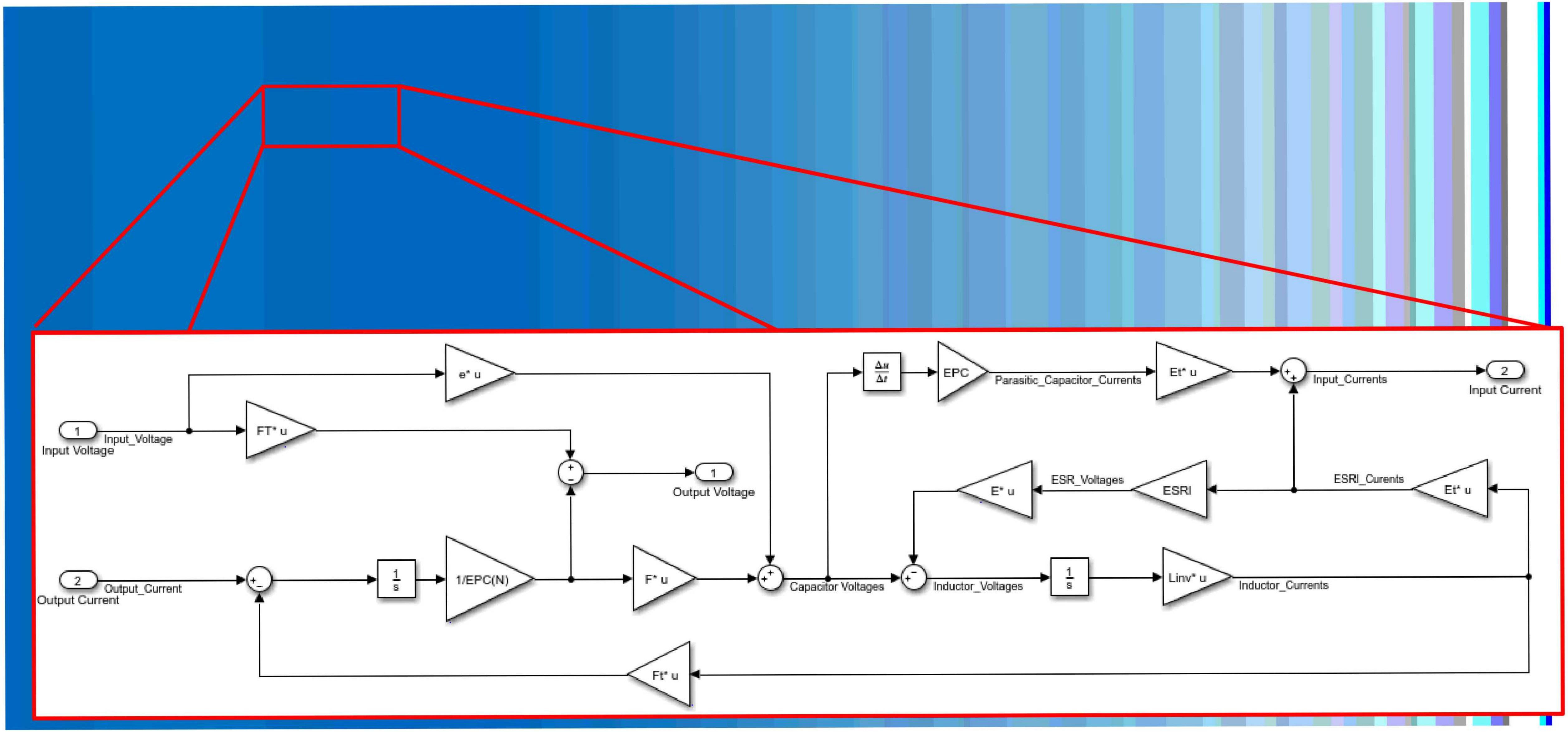
LTSpice



SIMULINK



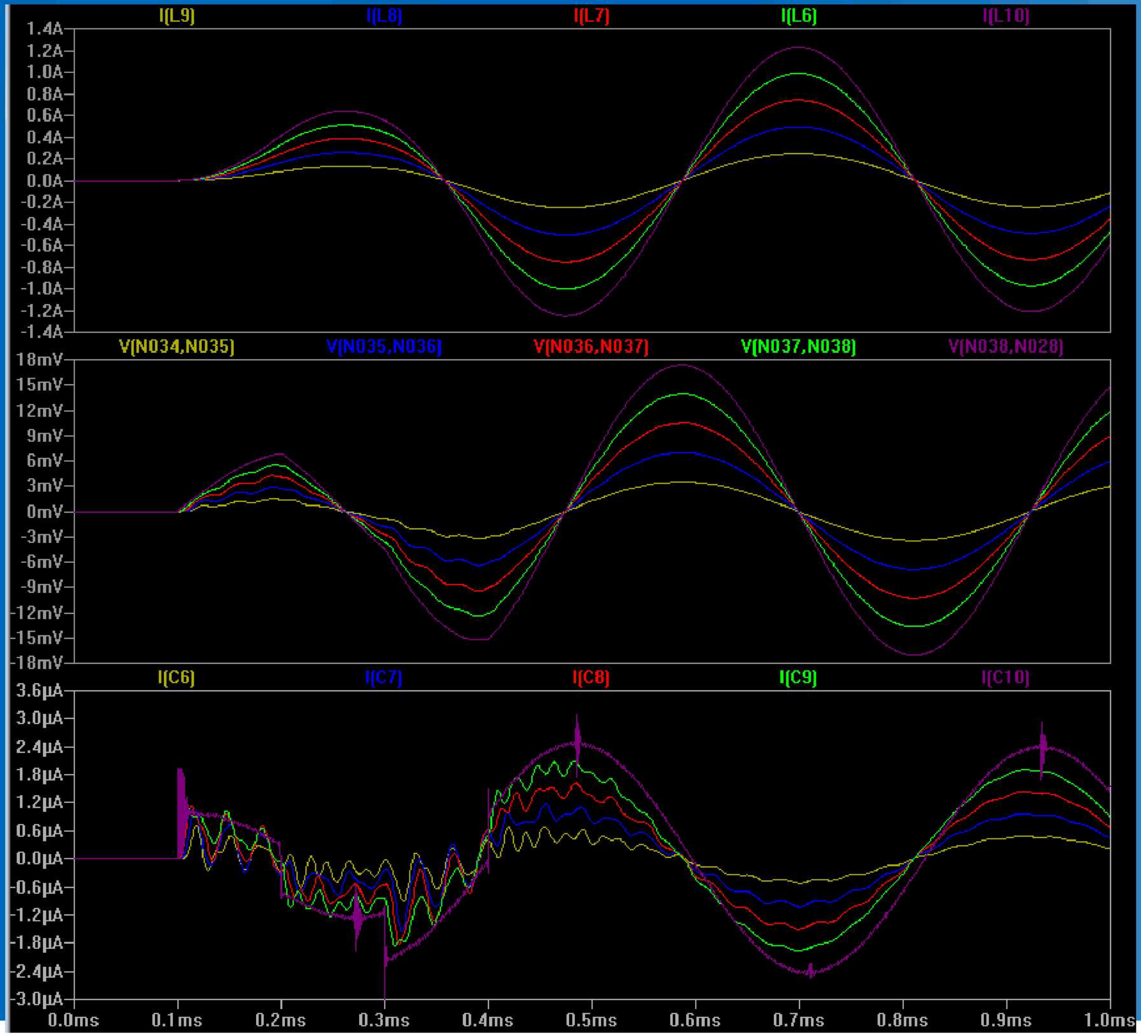
Electrical Modeling

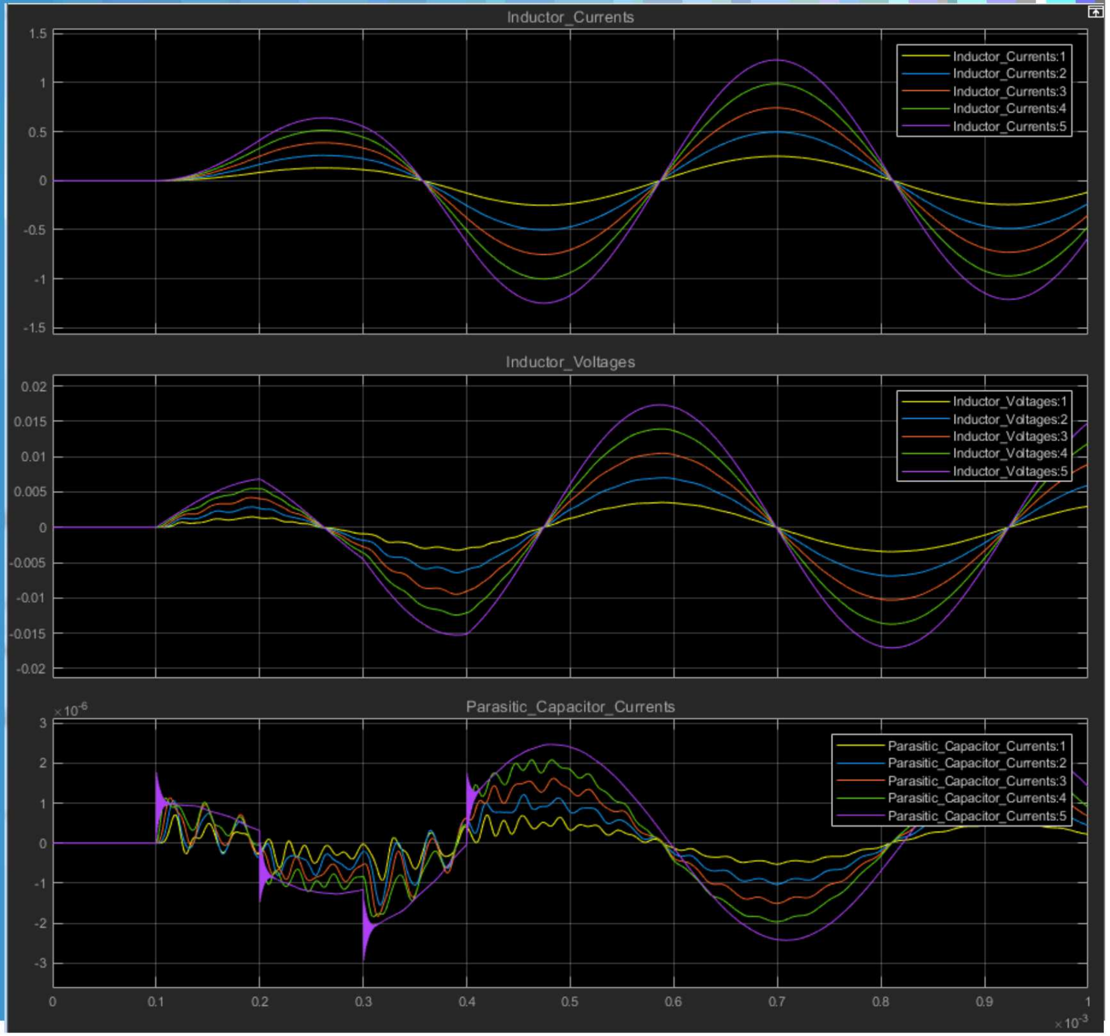


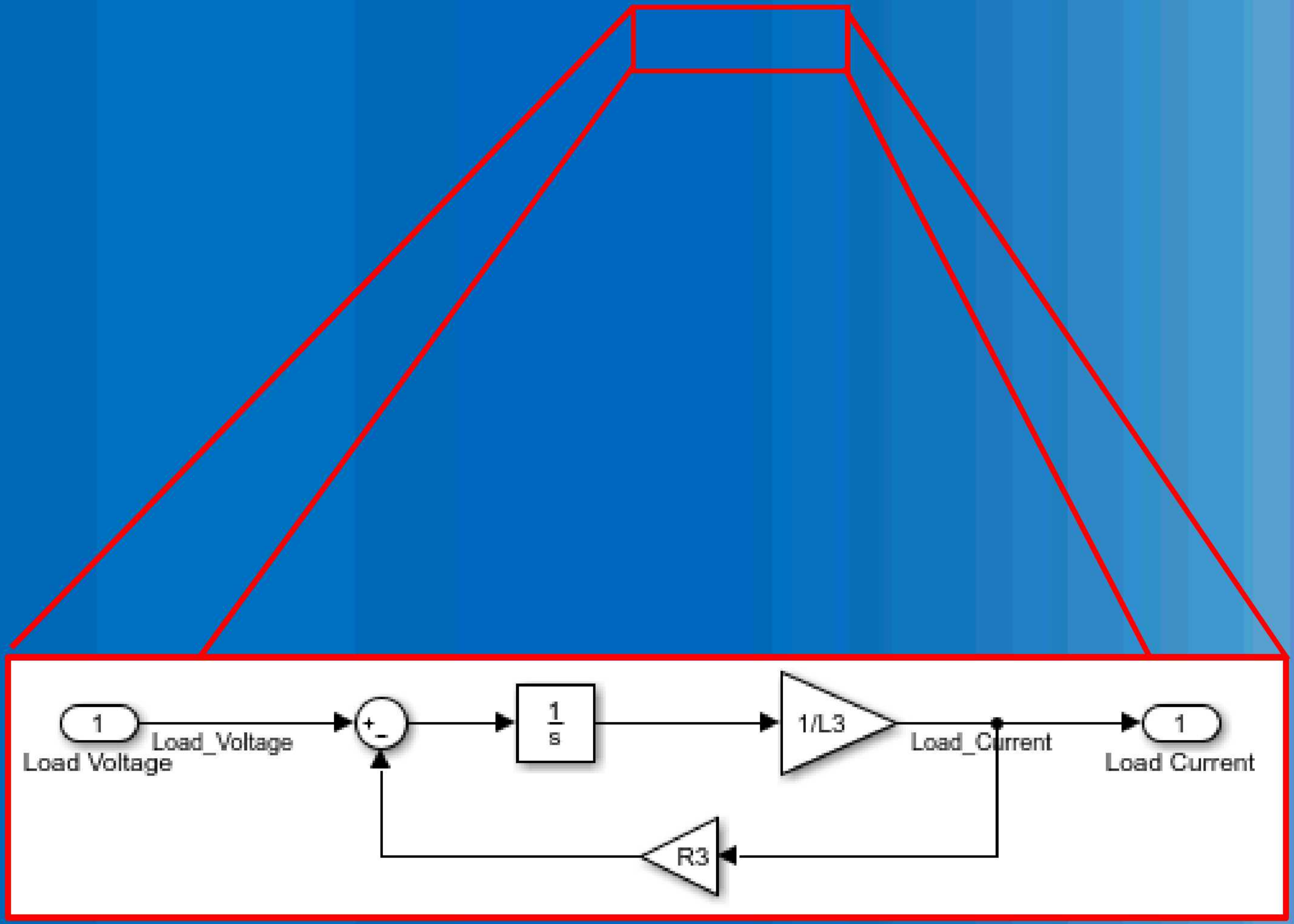
Electrical Modeling

LTSpice

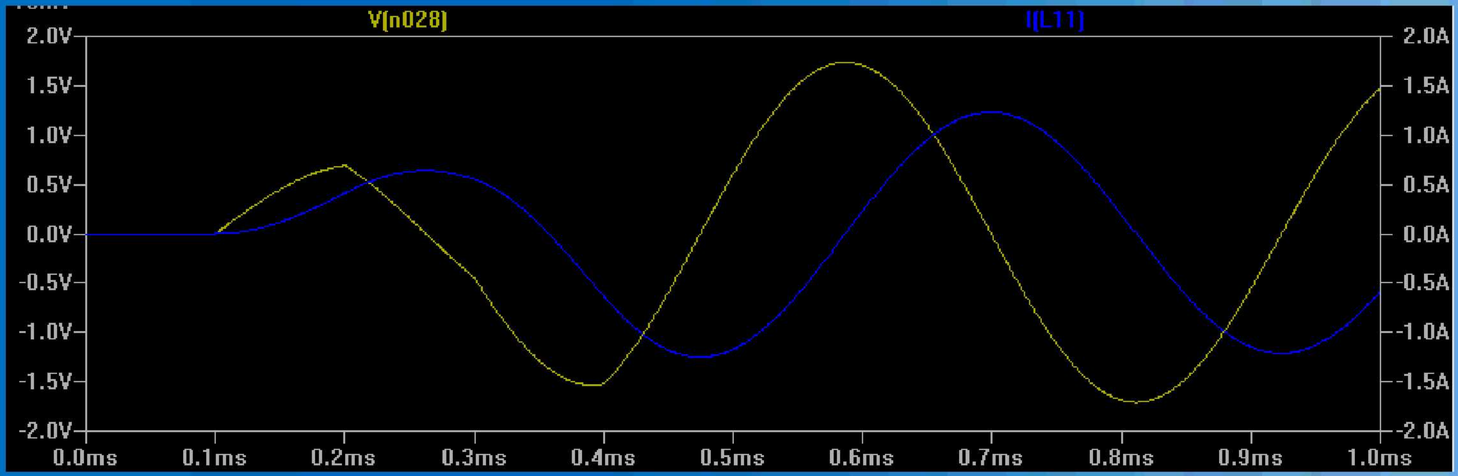
SIMULINK



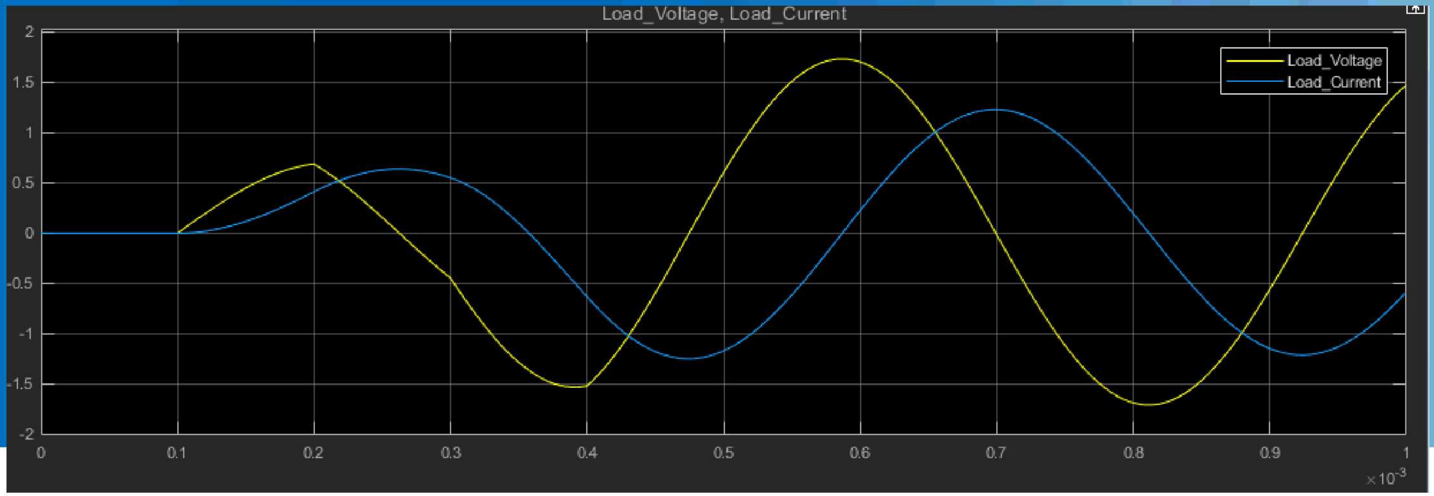



1
Load Voltage
Load_Voltage
+
-
1
s
1/L3
Load_Current
1
Load Current
R3

Electrical Modeling



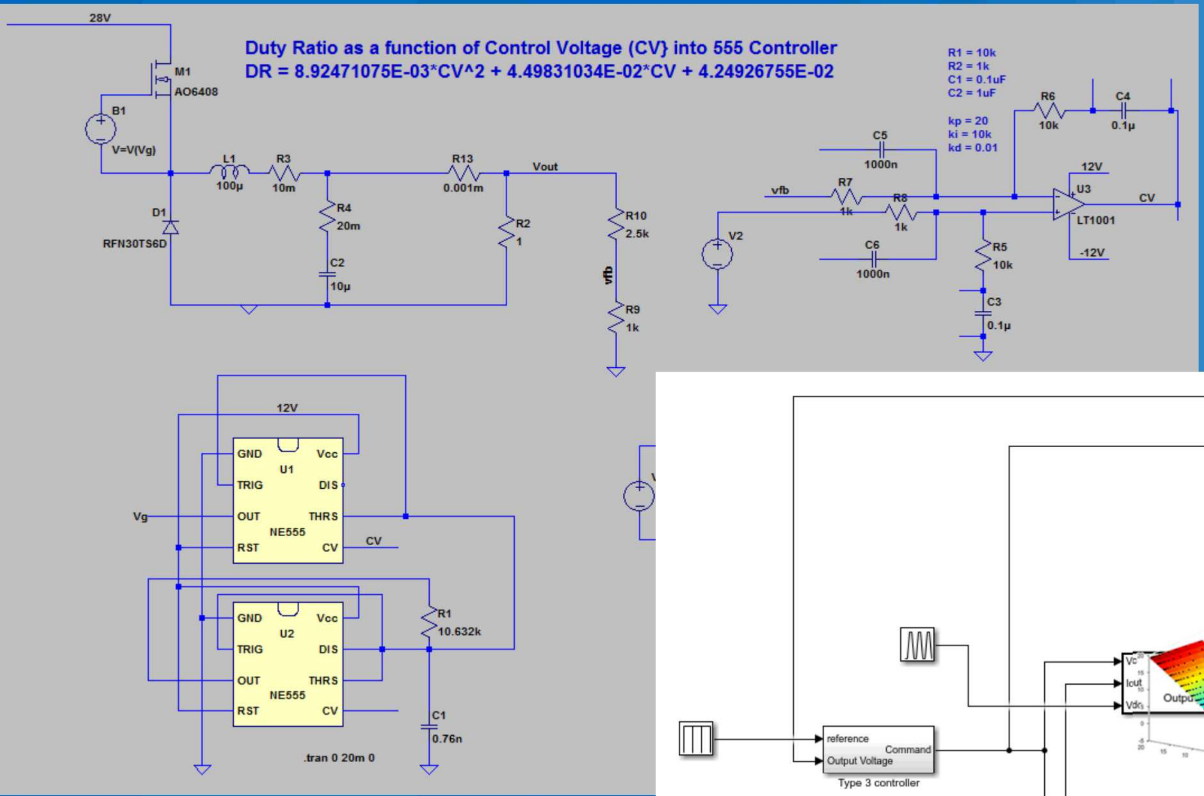
LTSpice



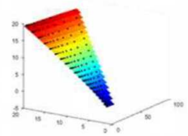
SIMULINK

Electrical Modeling – Power Converters

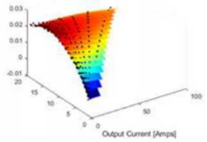
LTspice



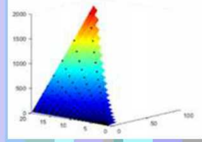
Output Voltage = f (Duty Ratio, Output Current)



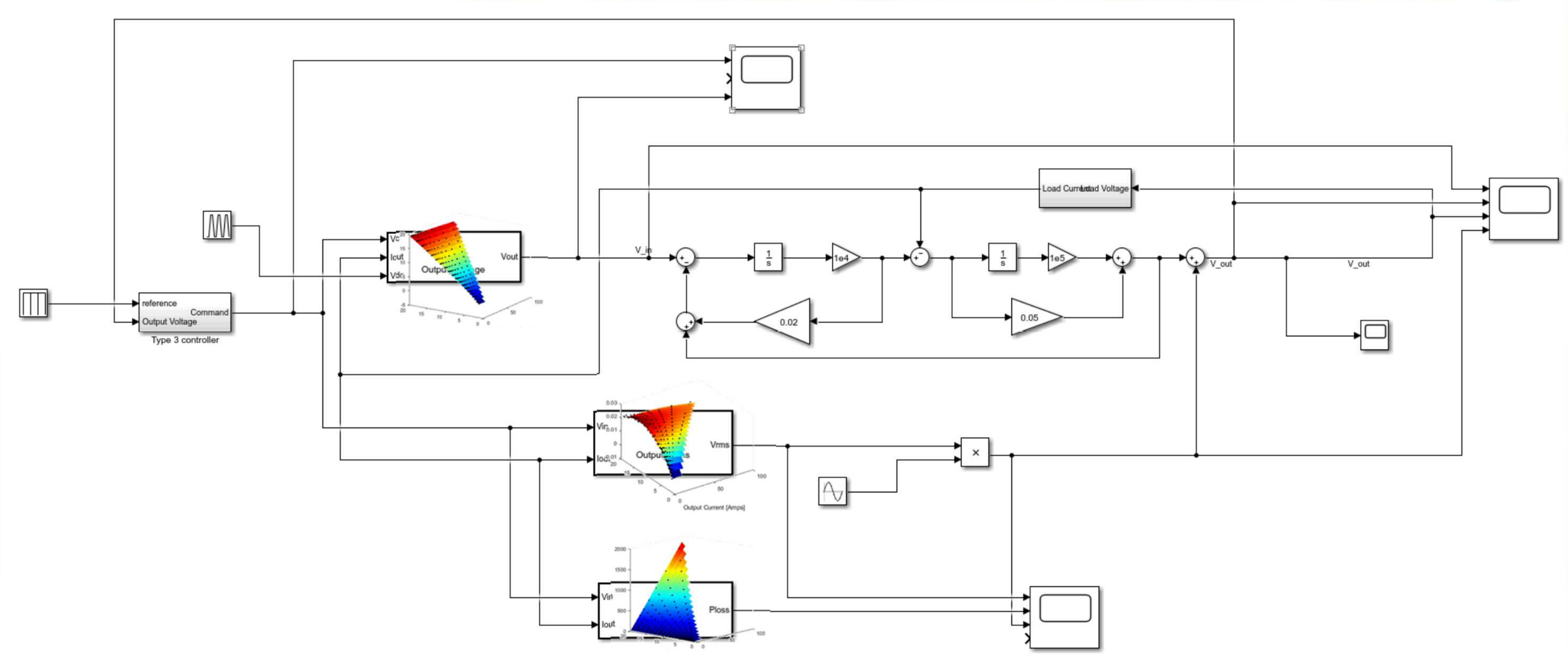
Output Voltage Ripple = f (Duty Ratio, Output Voltage)



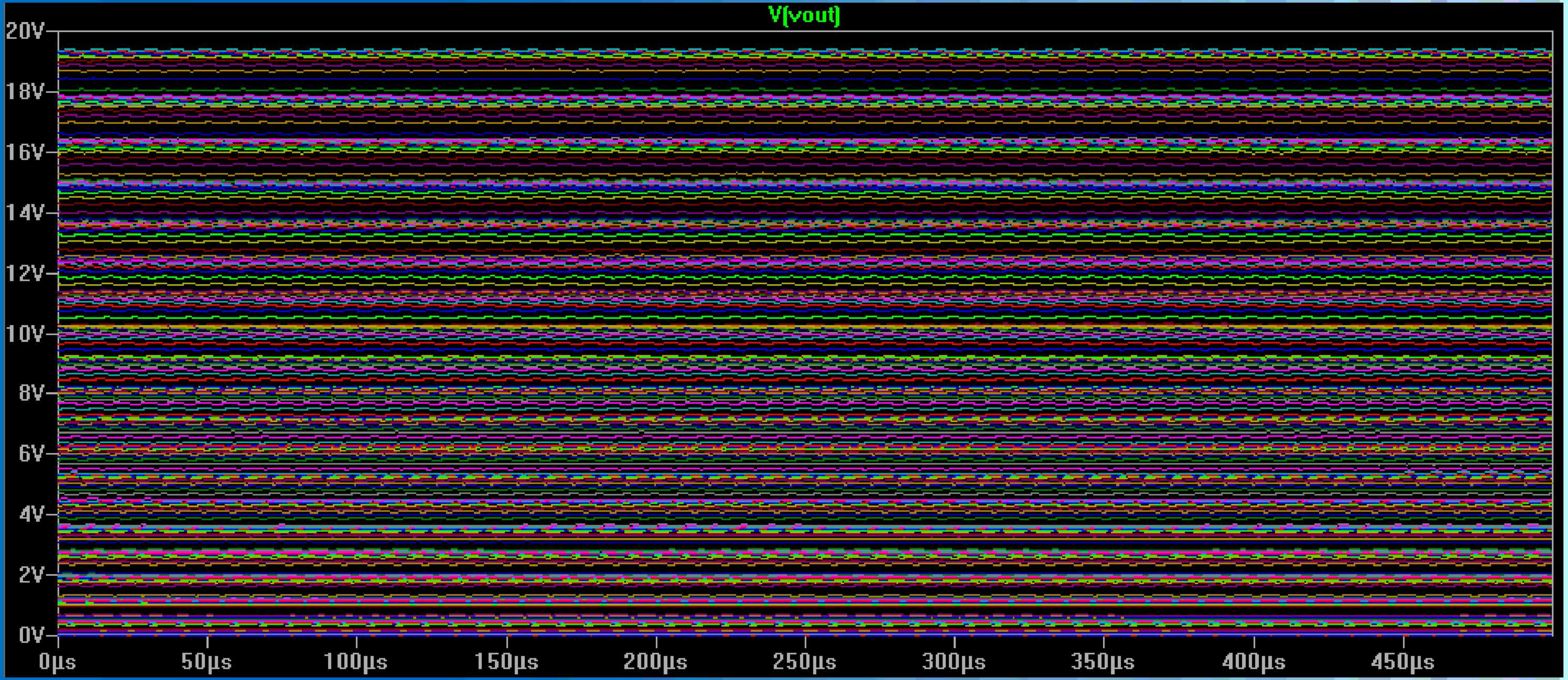
Power Loss = f (Duty Ratio, Output Voltage)



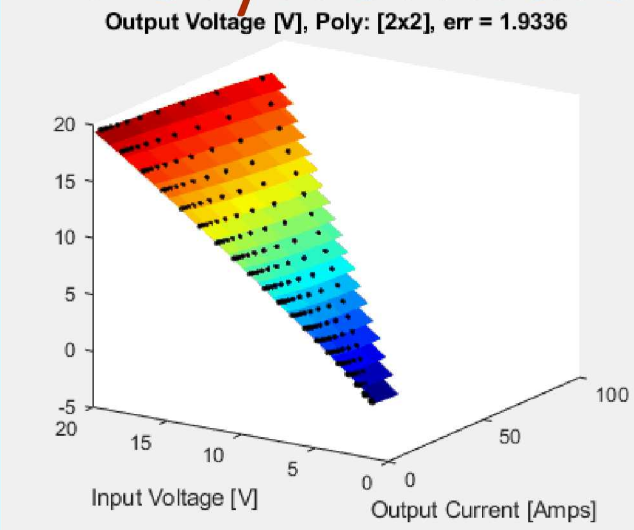
SIMULINK

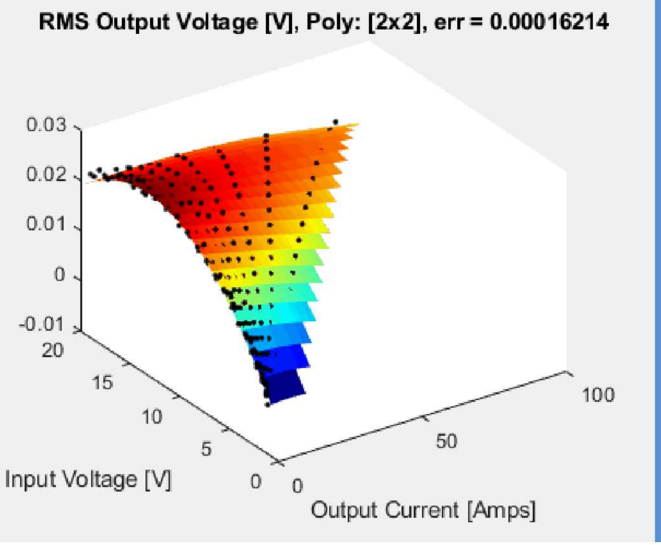


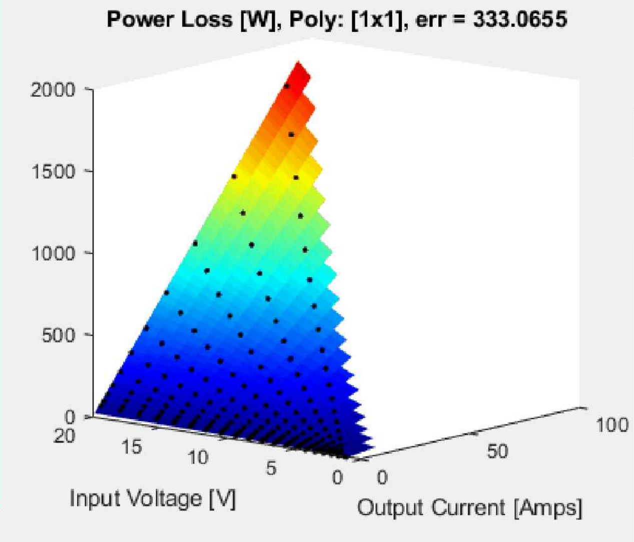
Sweeping Variables to extract Behavioral Parameters



Modeling Parameters as Multi-Dimensional Polynomials







$$\begin{bmatrix} 1.127e\text{-}06 & 2.411e\text{-}04 & -6.790e\text{-}03 \\ -7.693e\text{-}05 & -4.359e\text{-}03 & 1.162e{+}00 \\ 1.015e\text{-}03 & -2.069e\text{-}02 & -1.222e{+}00 \end{bmatrix}$$

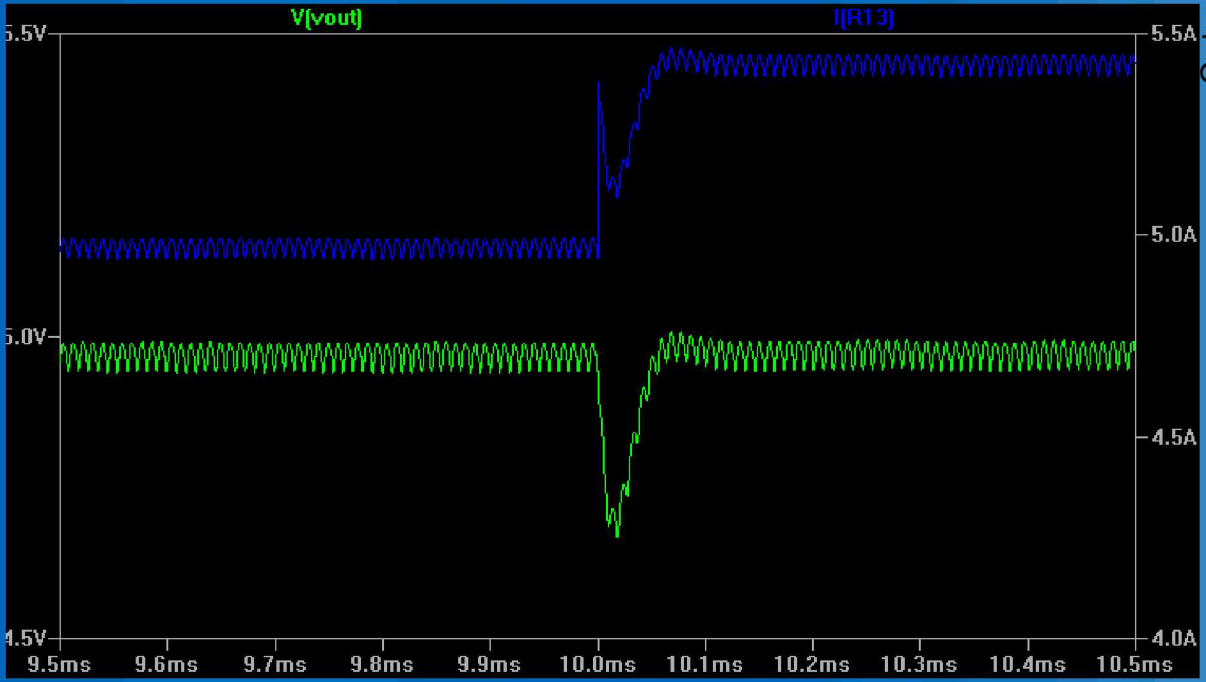
$$\begin{bmatrix} -3.219e\text{-}08 & 2.222e\text{-}06 & -1.667e\text{-}04 \\ 8.7346e\text{-}07 & -4.856e\text{-}05 & 4.504e\text{-}03 \\ -5.533e\text{-}06 & 1.205e\text{-}04 & -4.507e\text{-}03 \end{bmatrix}$$

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

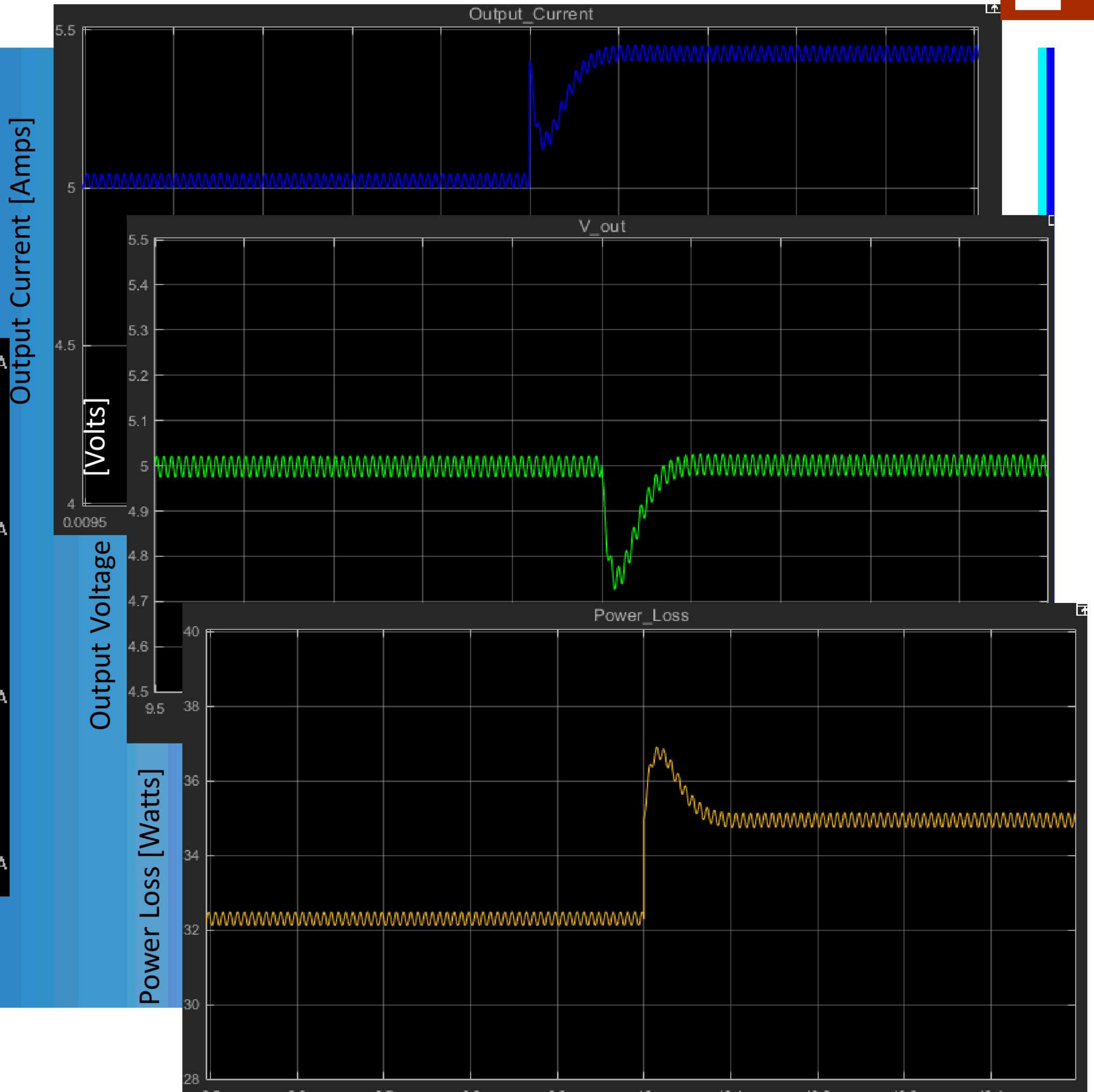
$$\begin{bmatrix} V_{in}^2 & V_{in} & 1 \end{bmatrix} \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} I_{out}^2 \\ I_{out} \\ 1 \end{bmatrix} = \begin{matrix} A_{11}V_{in}^2 I_{out}^2 + A_{12}V_{in}^2 I_{out} + A_{13}V_{in}^2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

Power Converter Modeling Results

LTspice

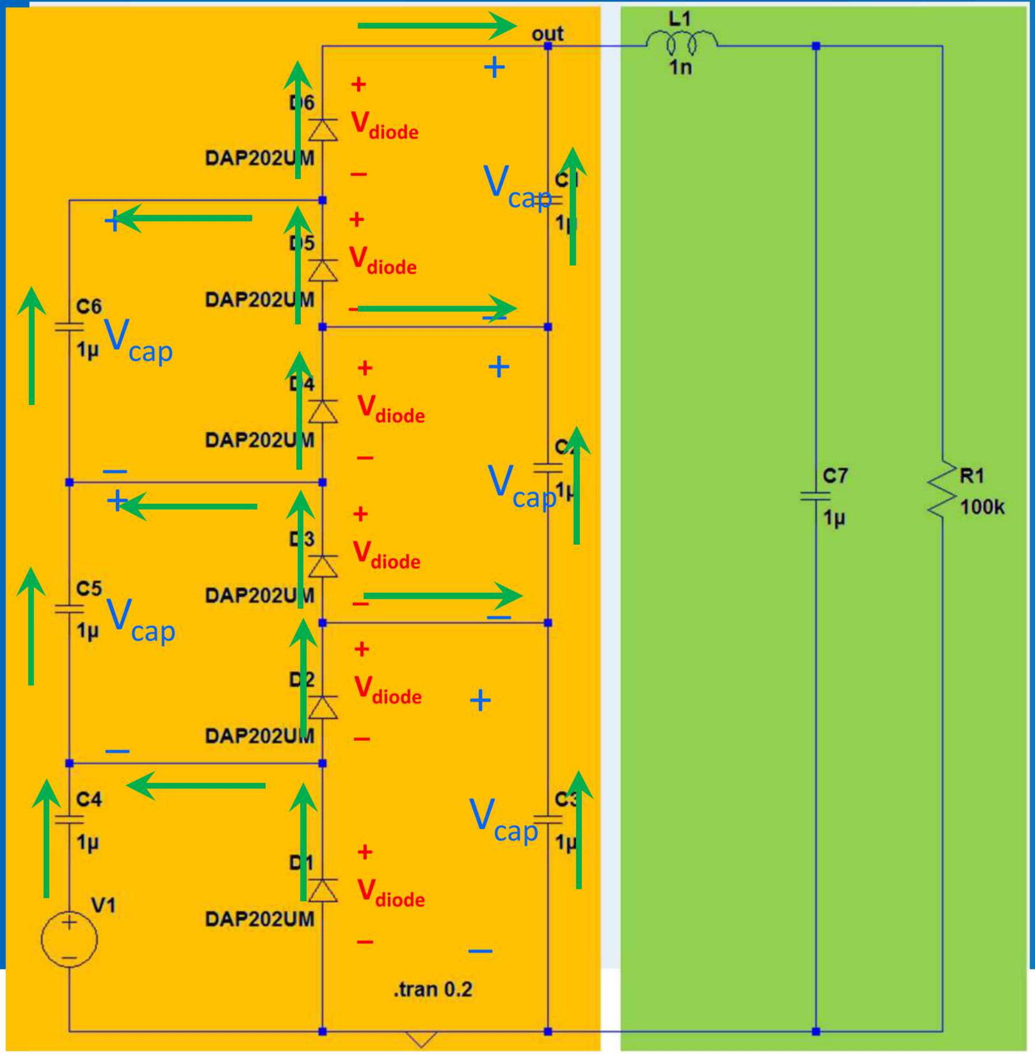


SIMULINK



Electrical Modeling - Charge Pump

Charge Pump LTspice Load

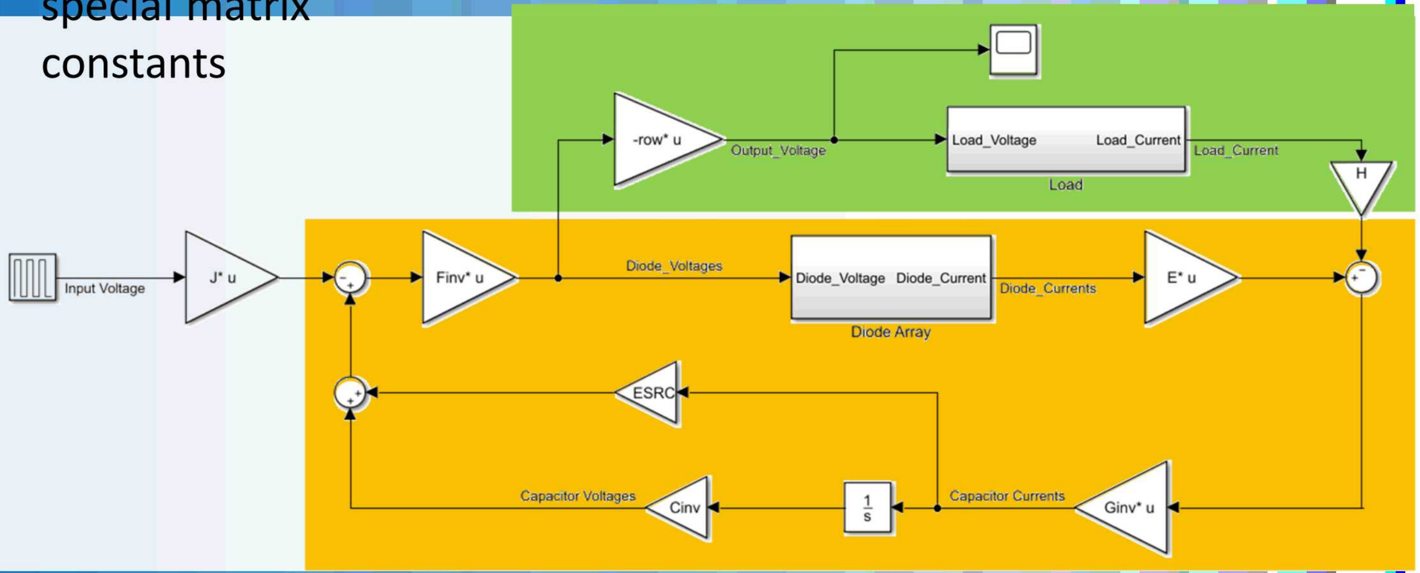


Model Topologies

Topologies with repetitions use special matrix constants

SIMULINK

Load

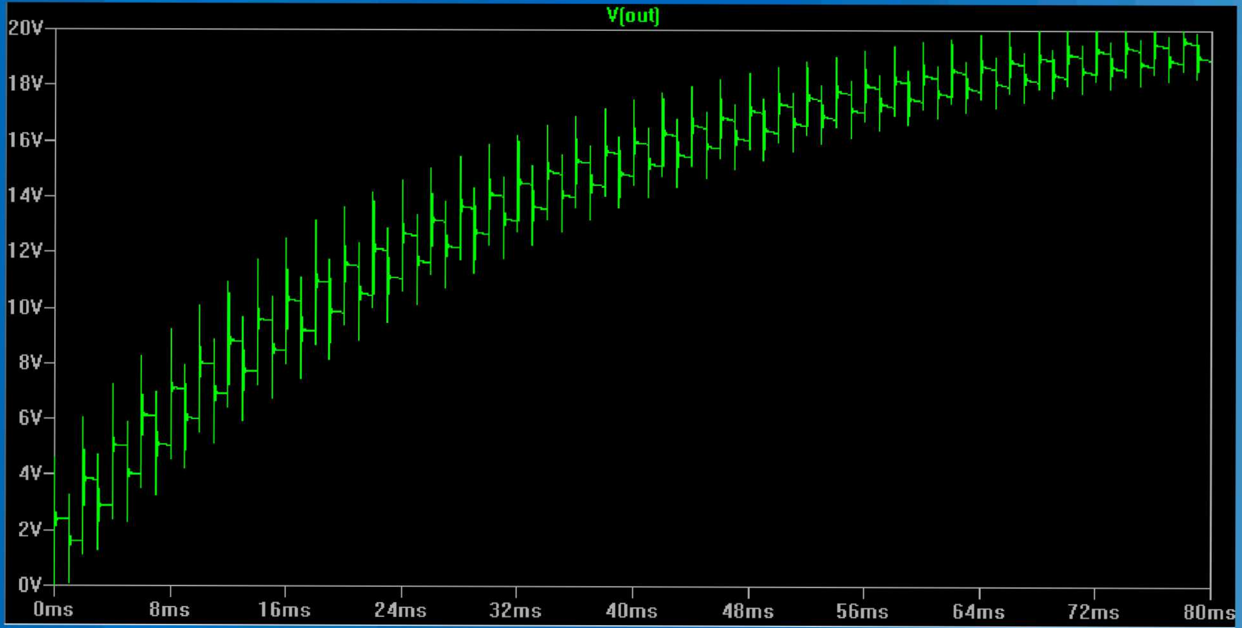


Charge Pump

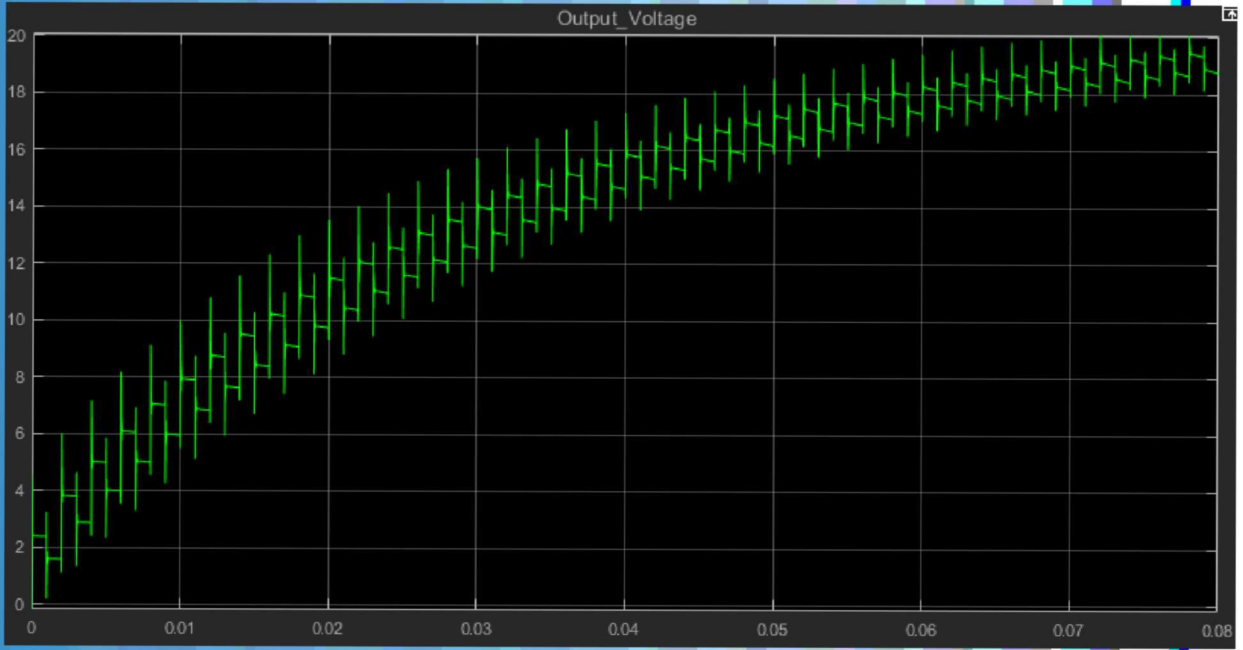
Charge Pump Modeling Results

Output Voltage

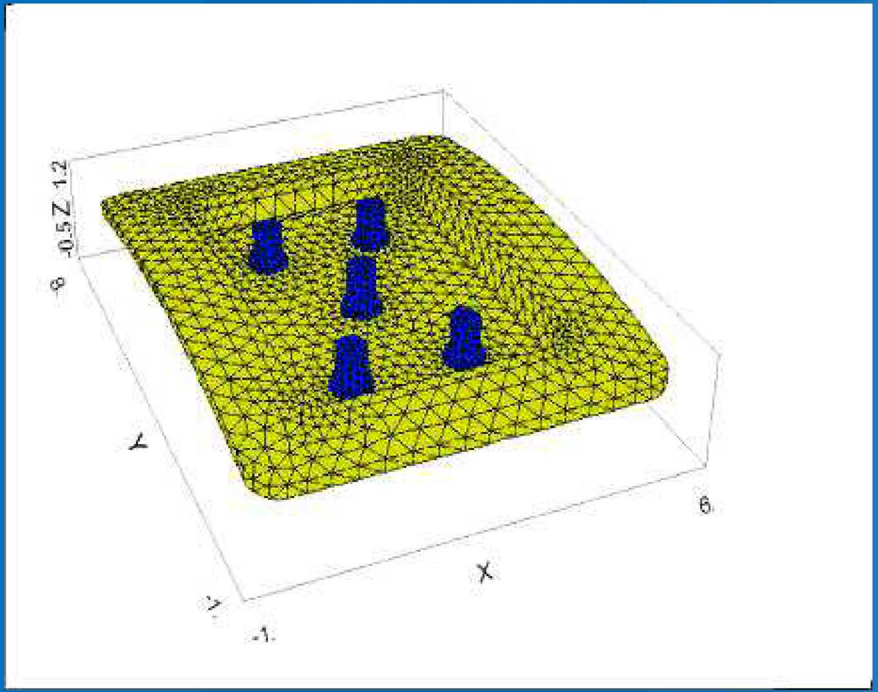
LTspice



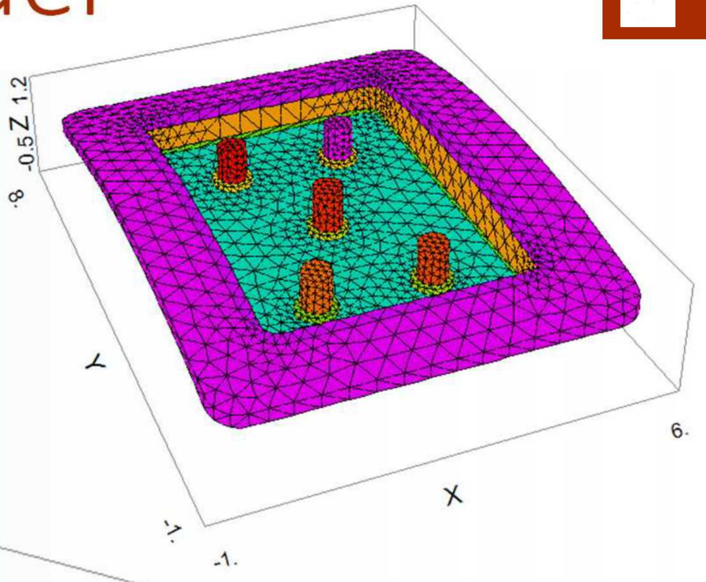
SIMULINK

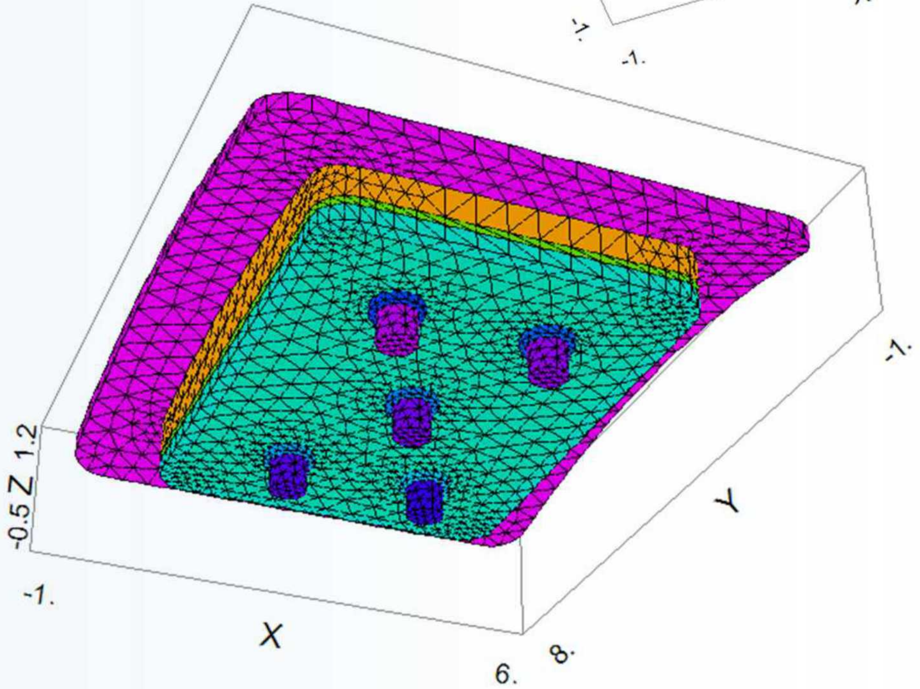


Physics Model - Finite Element Model

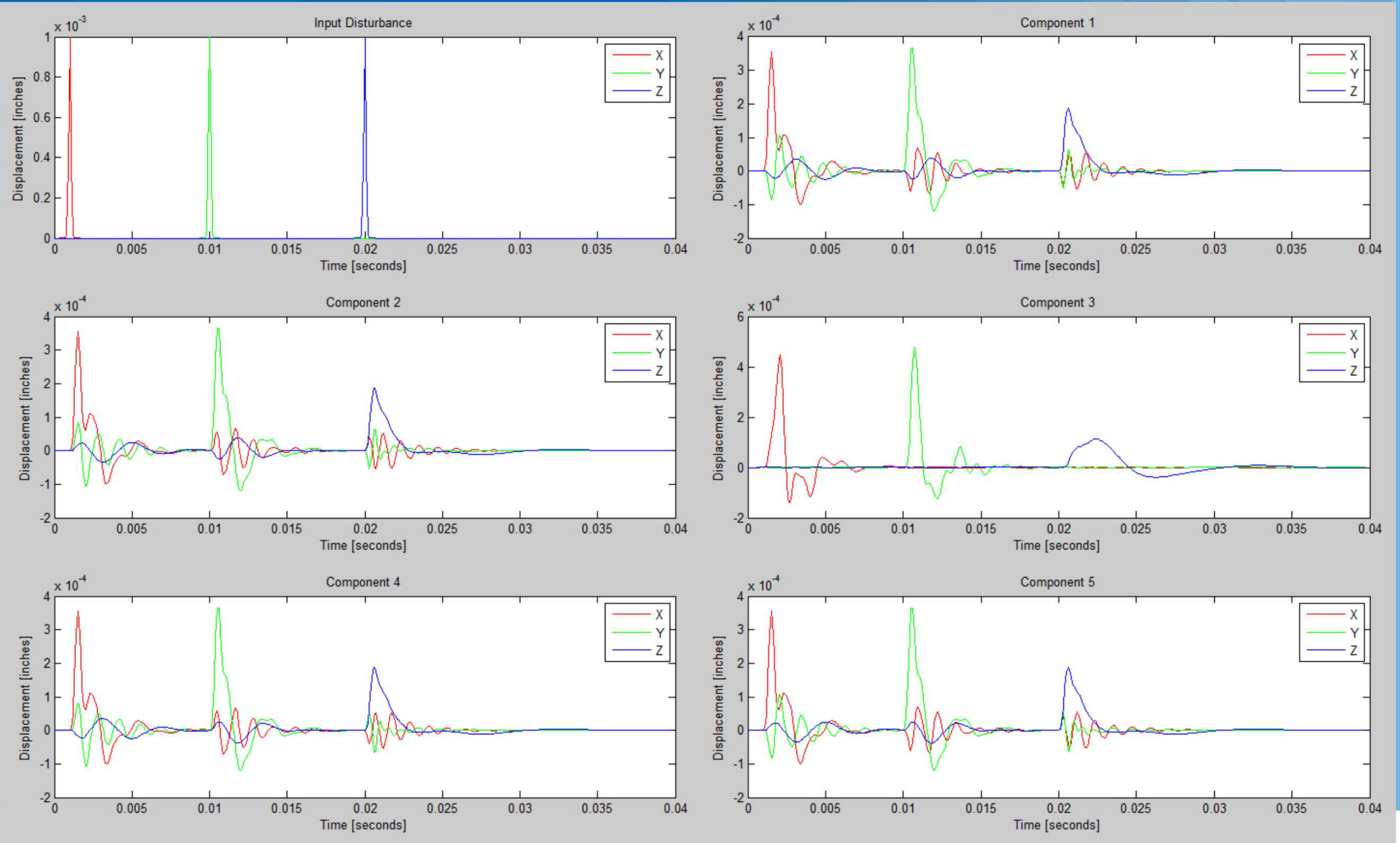


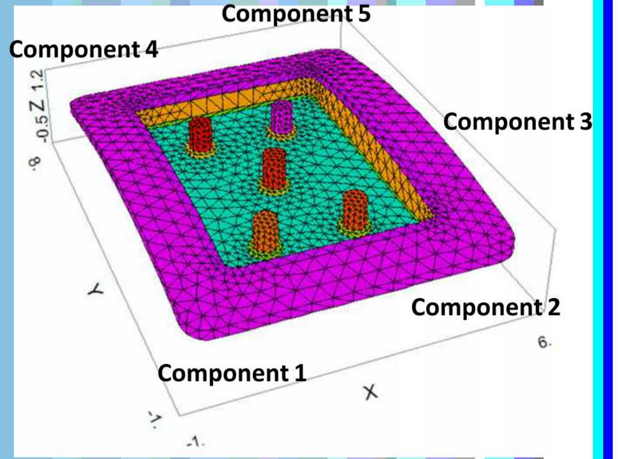
[Click on Video]



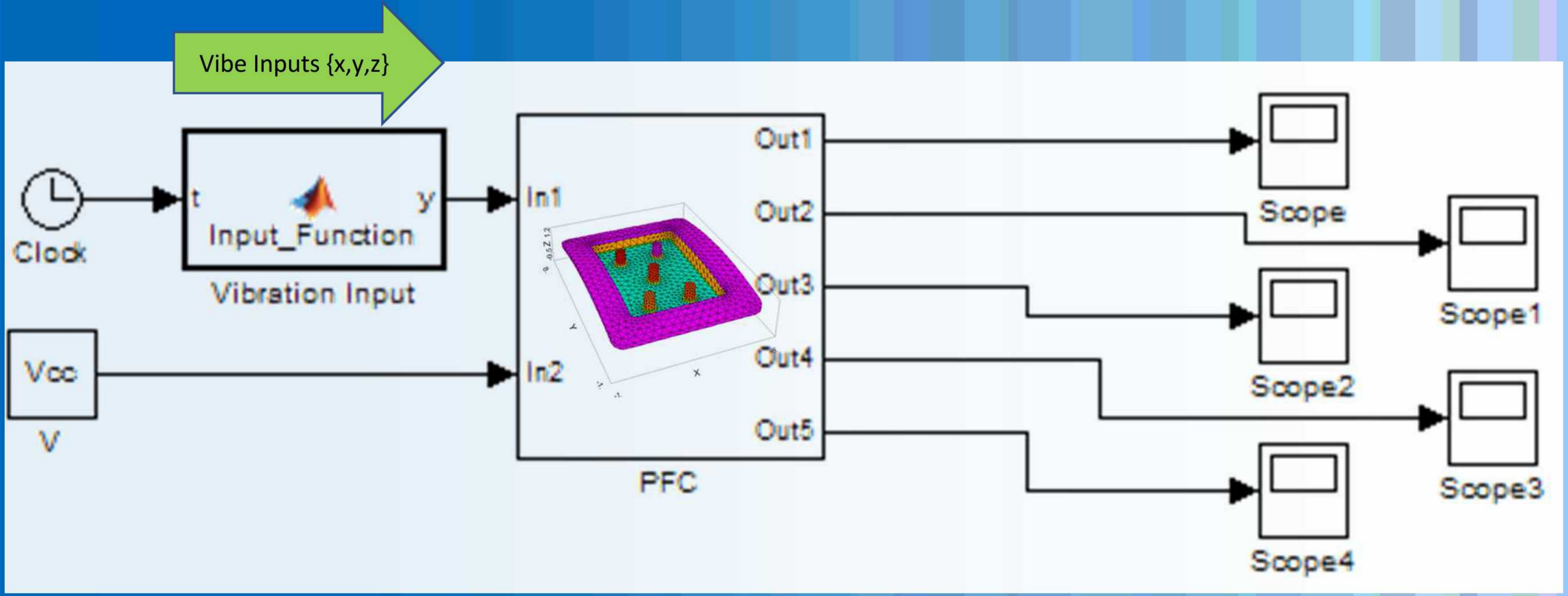


PFC Model – Shock/Vibe

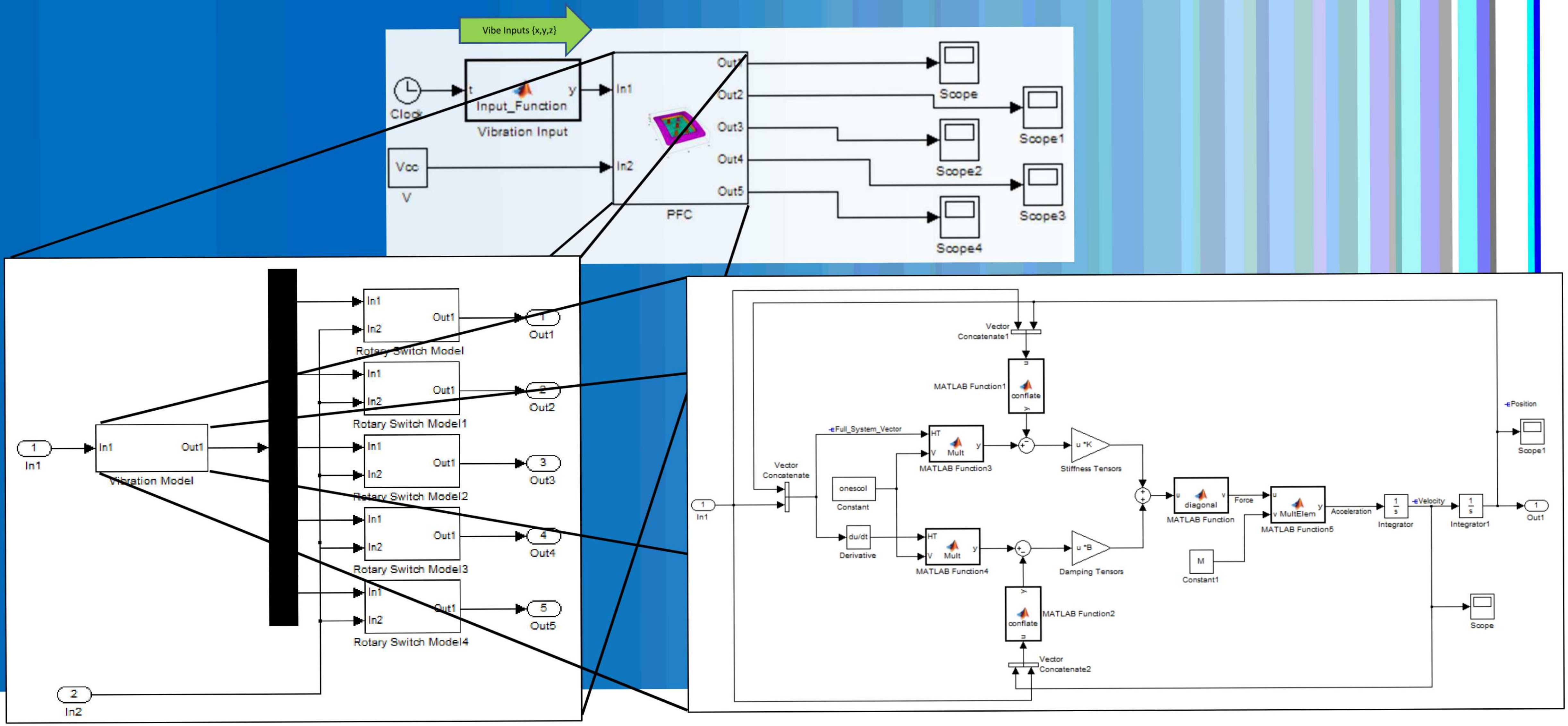




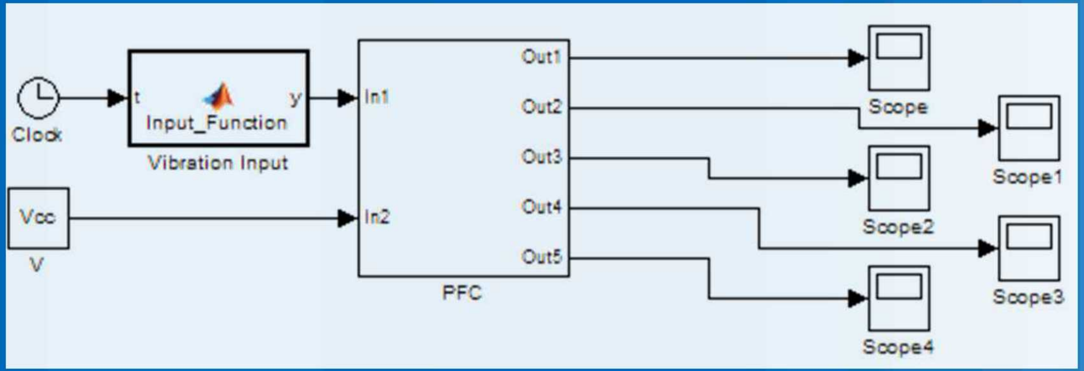
Top Level Simulink Model for Reduced Order

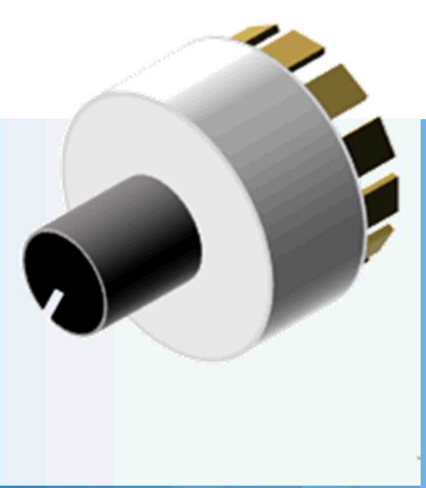


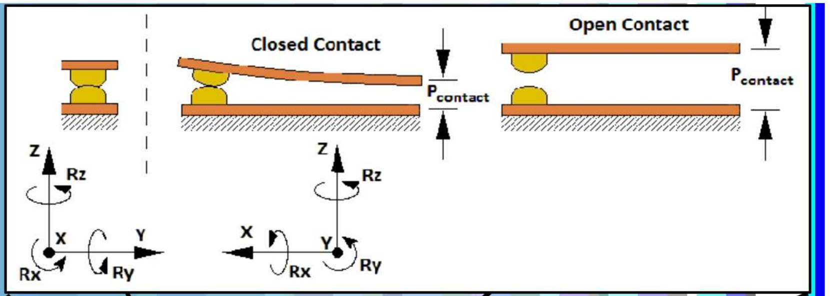
Simulink Model Reduced Order Shock/Vibration

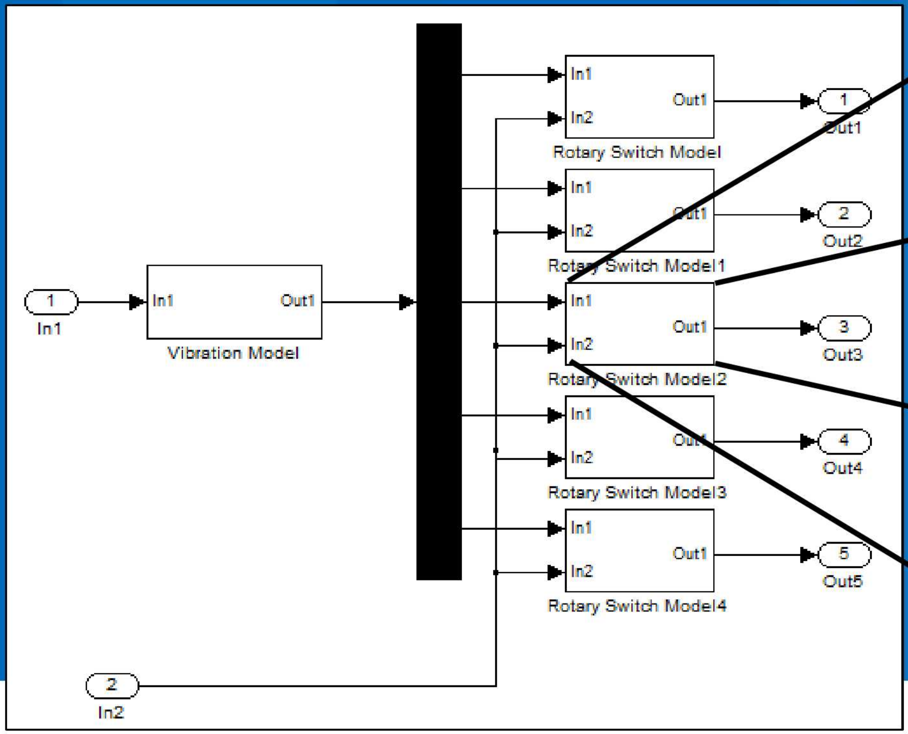


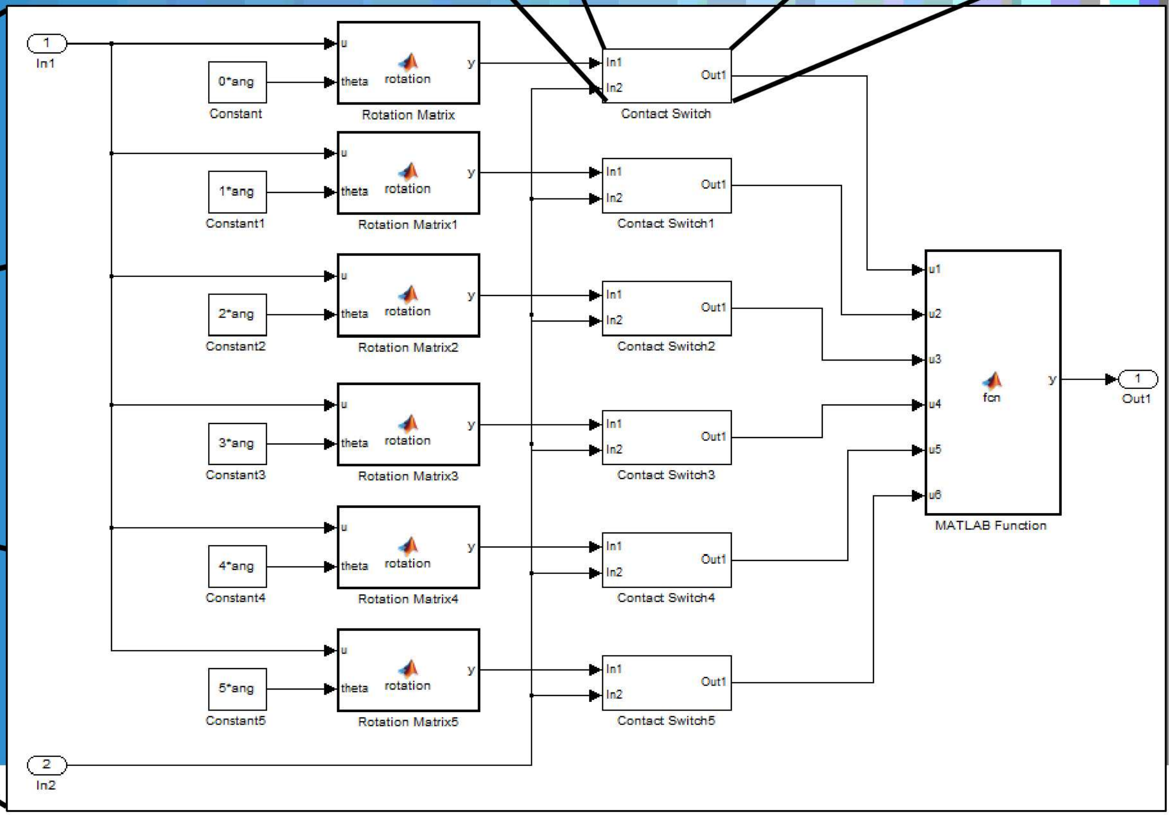
PFC - Simulink Model



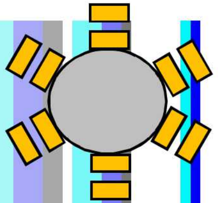








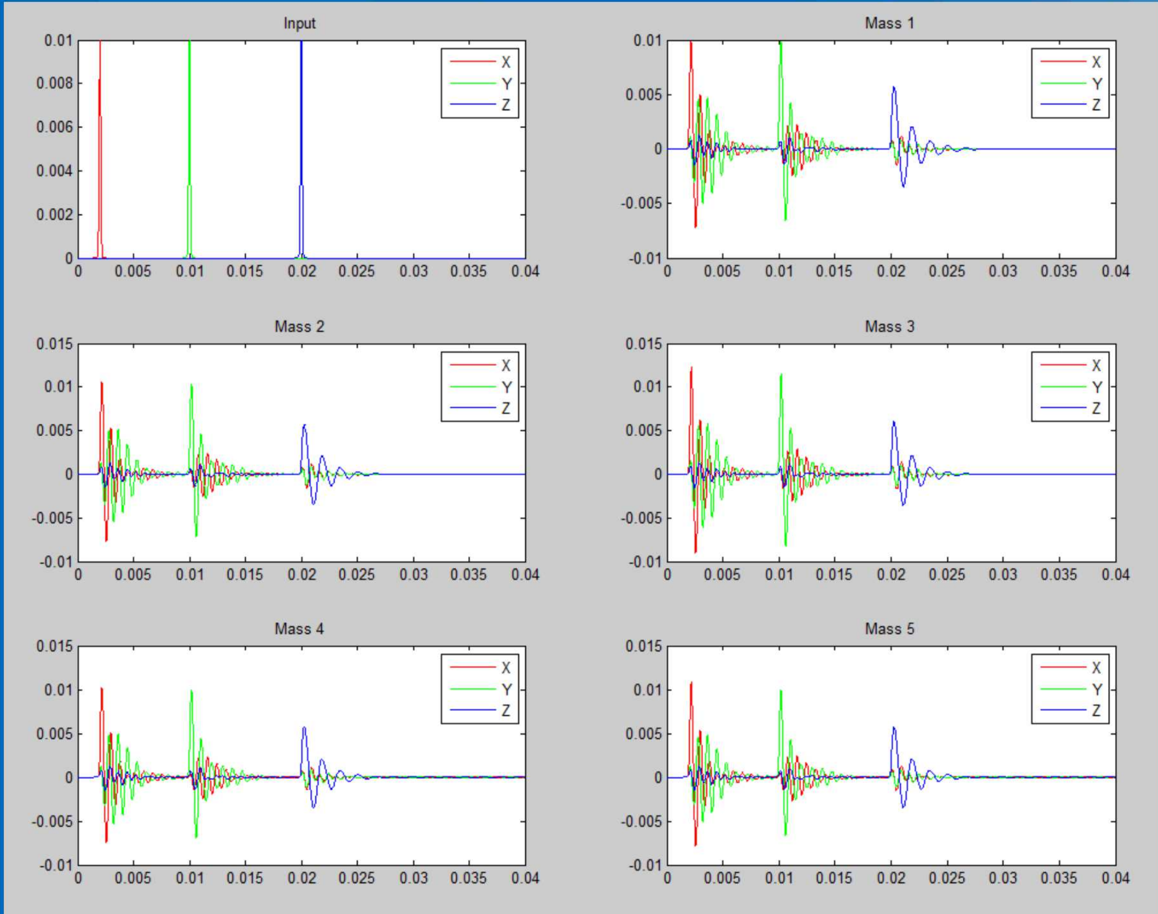
Simplified Five-Mass Model



Acceleration at each connector on component 1

Each component has six contacts at 60^o orientation

Dynamics of each mass

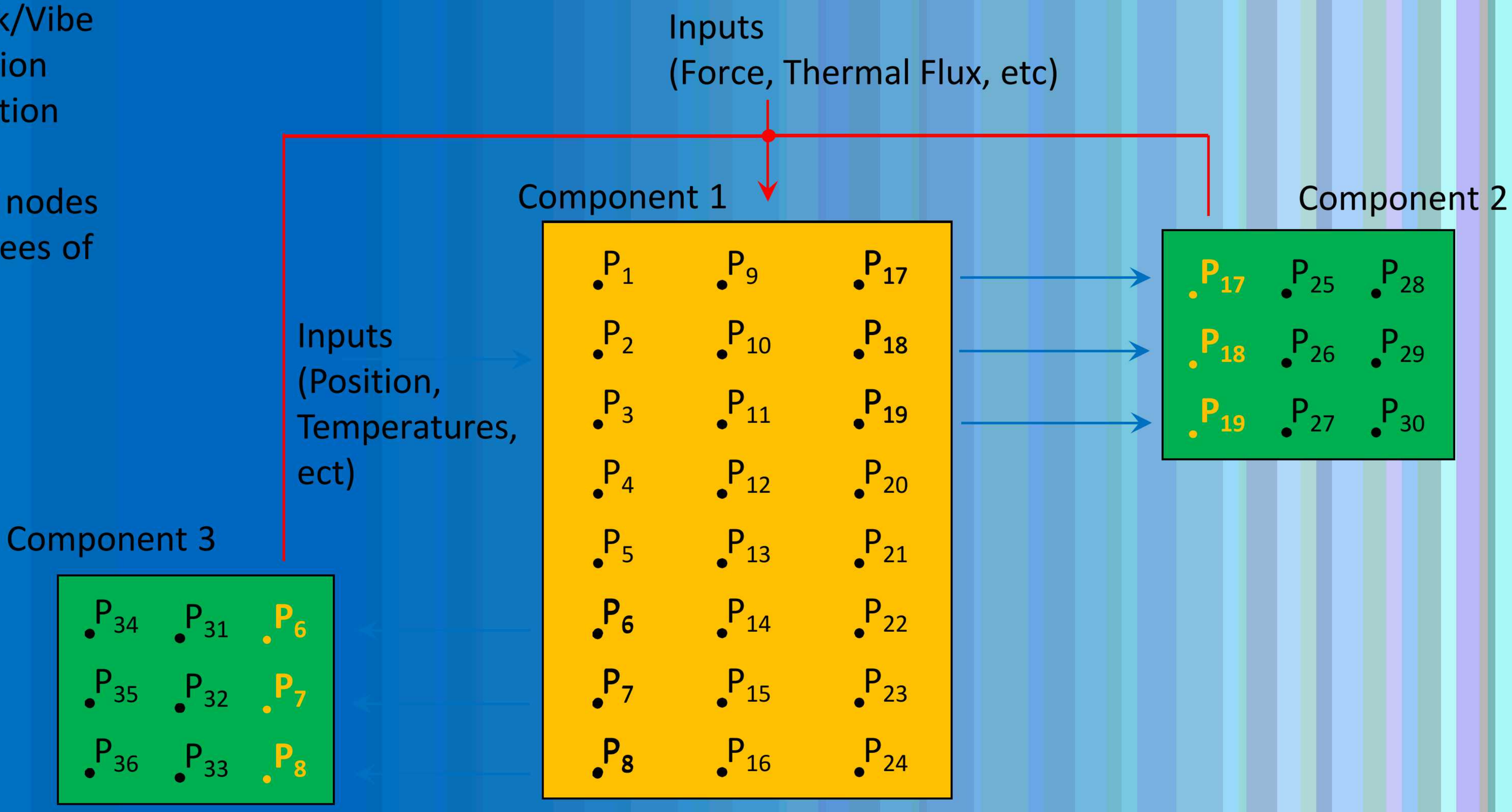


Connecting Linear Continuous Time Models

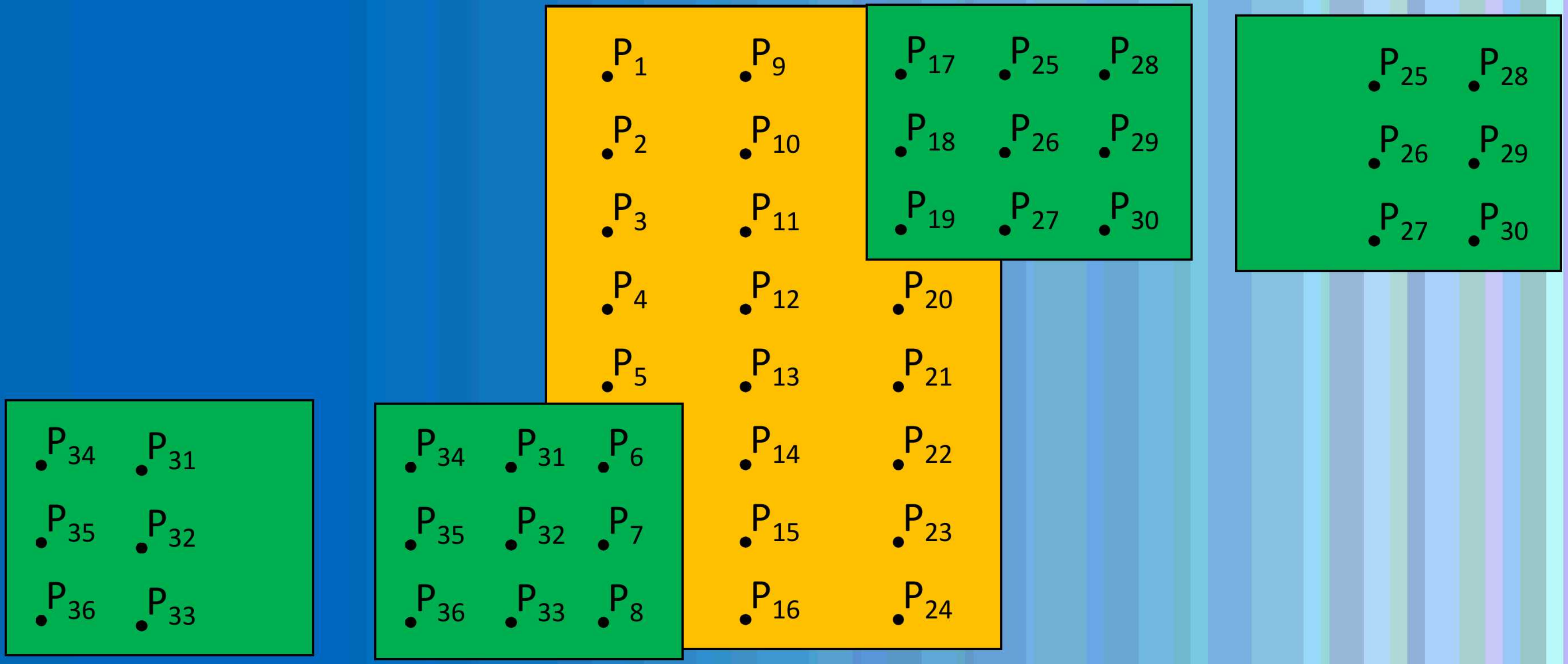
Mechanical Shock/Vibe
Thermal Conduction
Electrical Conduction

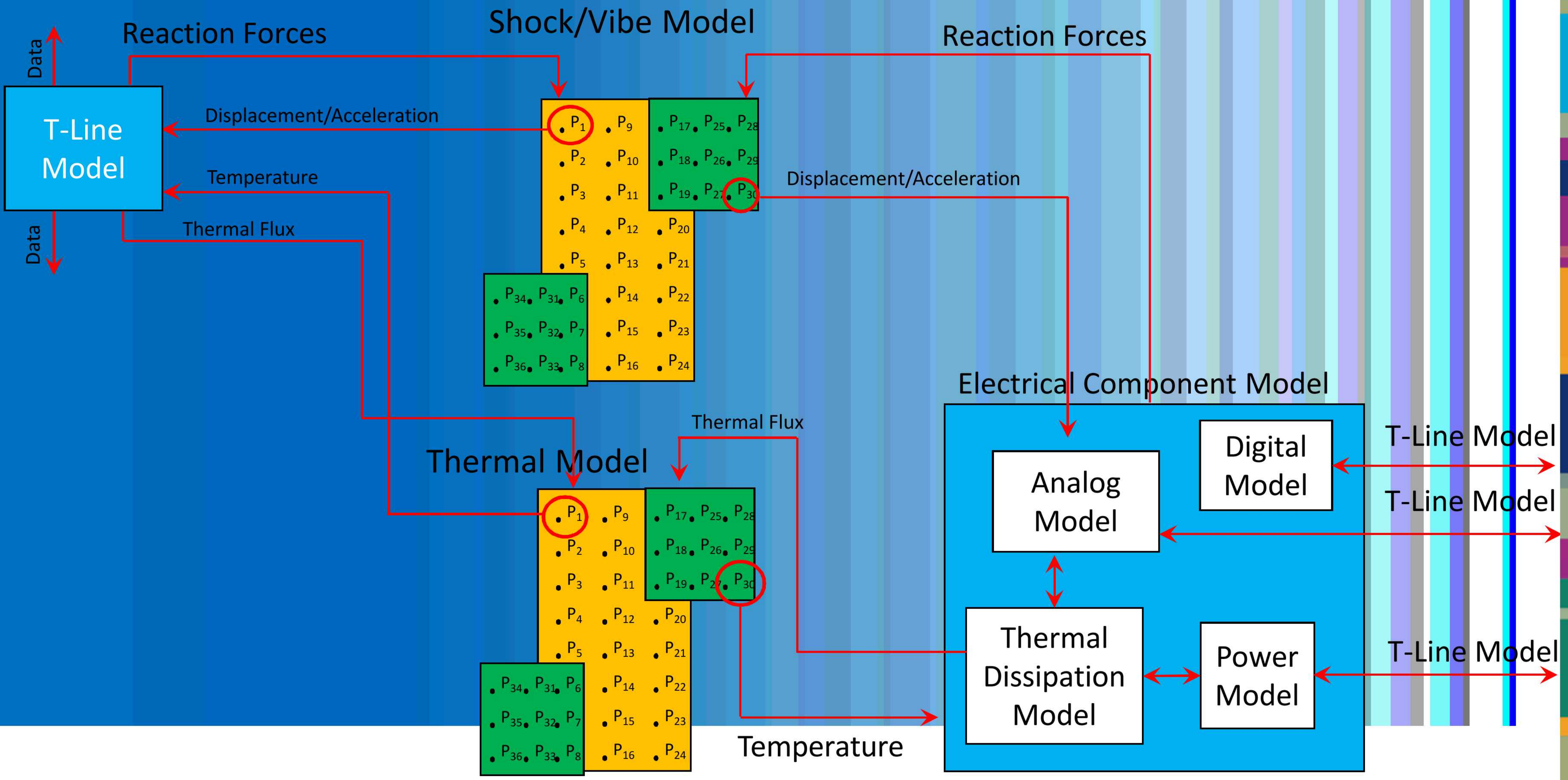
Points are spatial nodes with physics degrees of freedom:

- Temperature
- Displacement
- Voltage



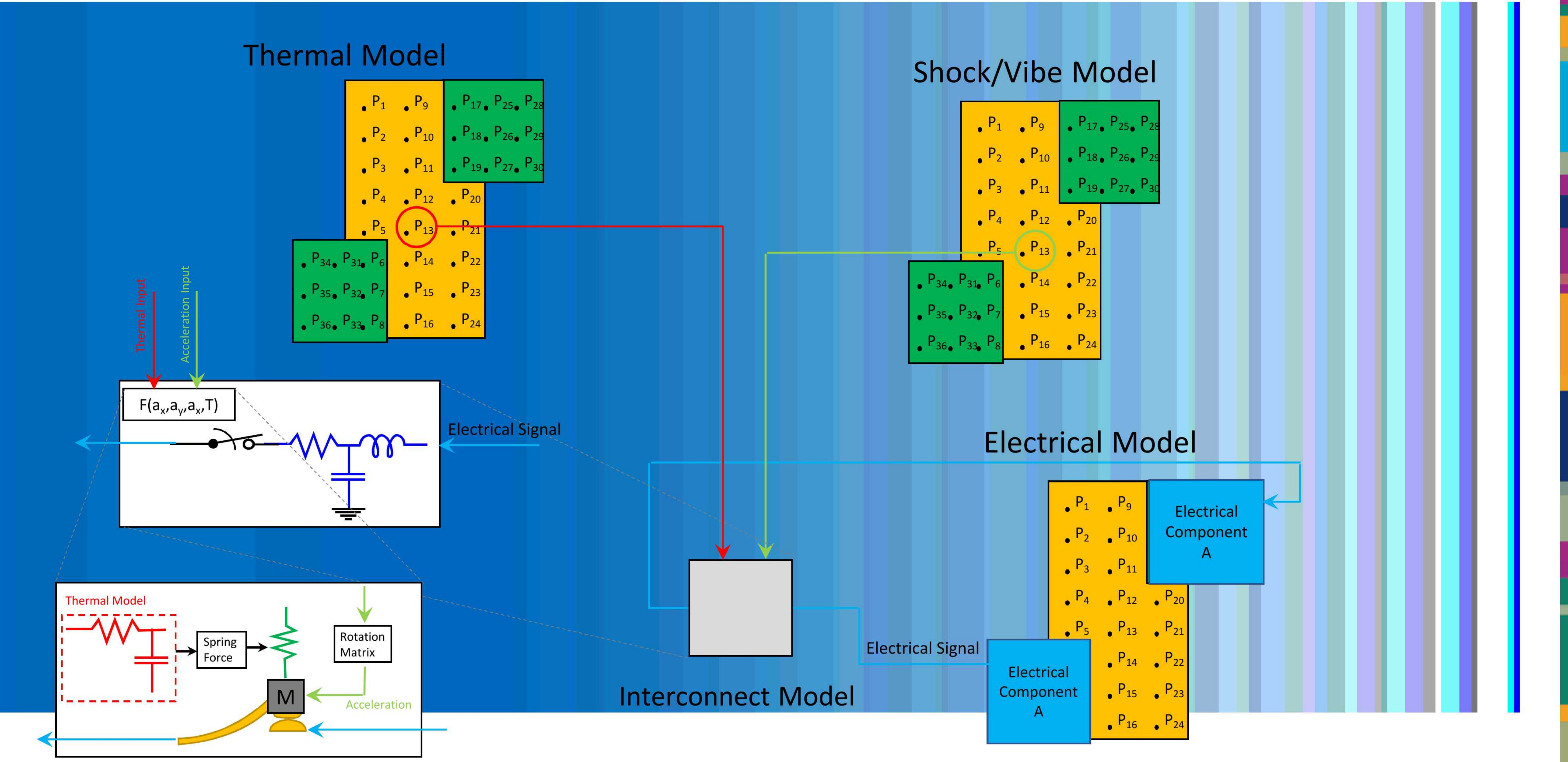
Connecting Linear Continuous Time Models



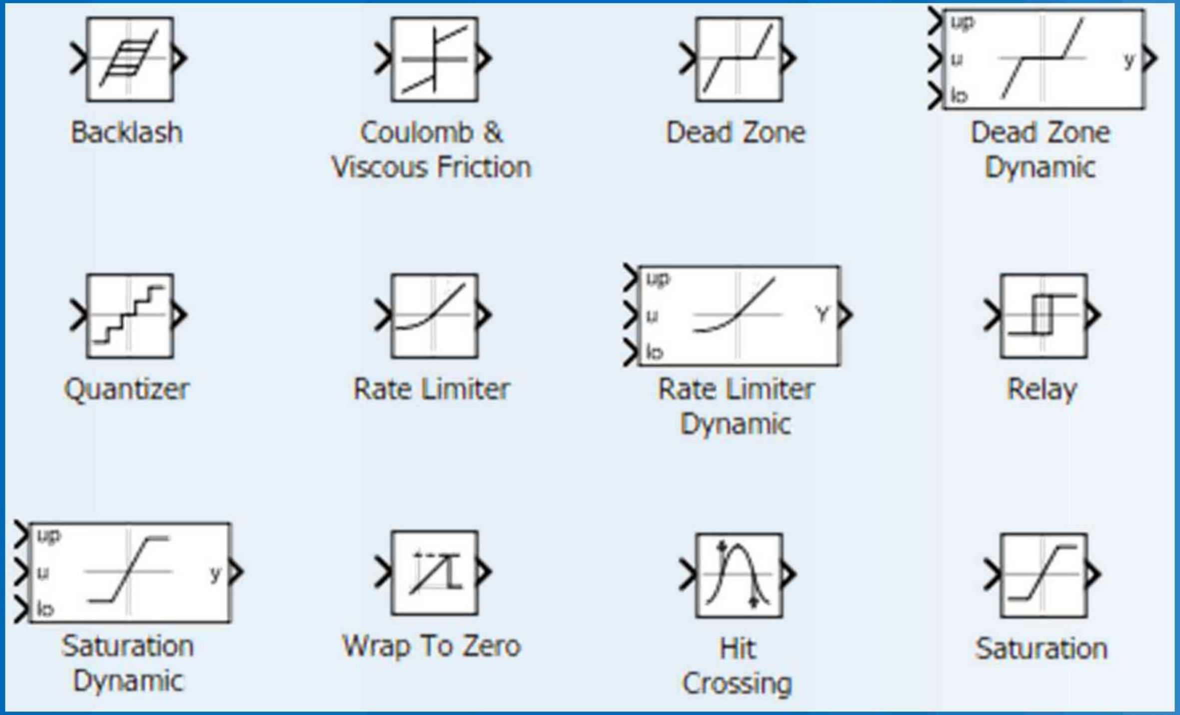


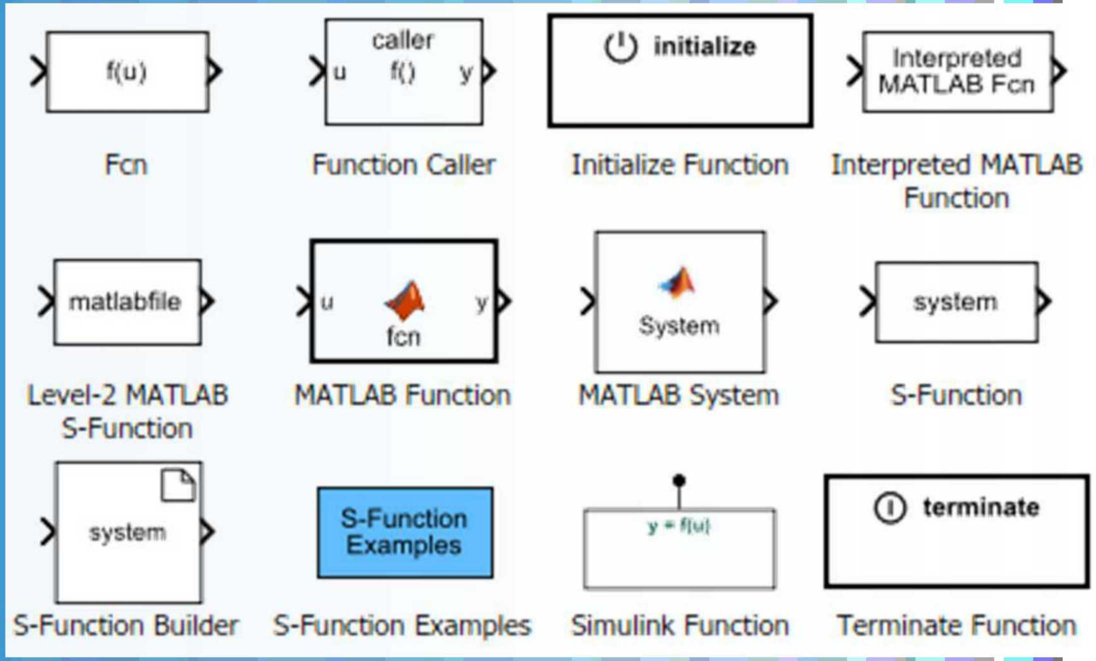
Reaction Forces
Shock/Vibe Model
Reaction Forces
Data
T-Line Model
Displacement/Acceleration
Temperature
Thermal Flux
Data
Displacement/Acceleration
Electrical Component Model
Thermal Flux
Thermal Model
Analog Model
Digital Model
T-Line Model
T-Line Model
Thermal Dissipation Model
Power Model
T-Line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

Modeling Interconnects in System Model



Modeling Nonlinearities





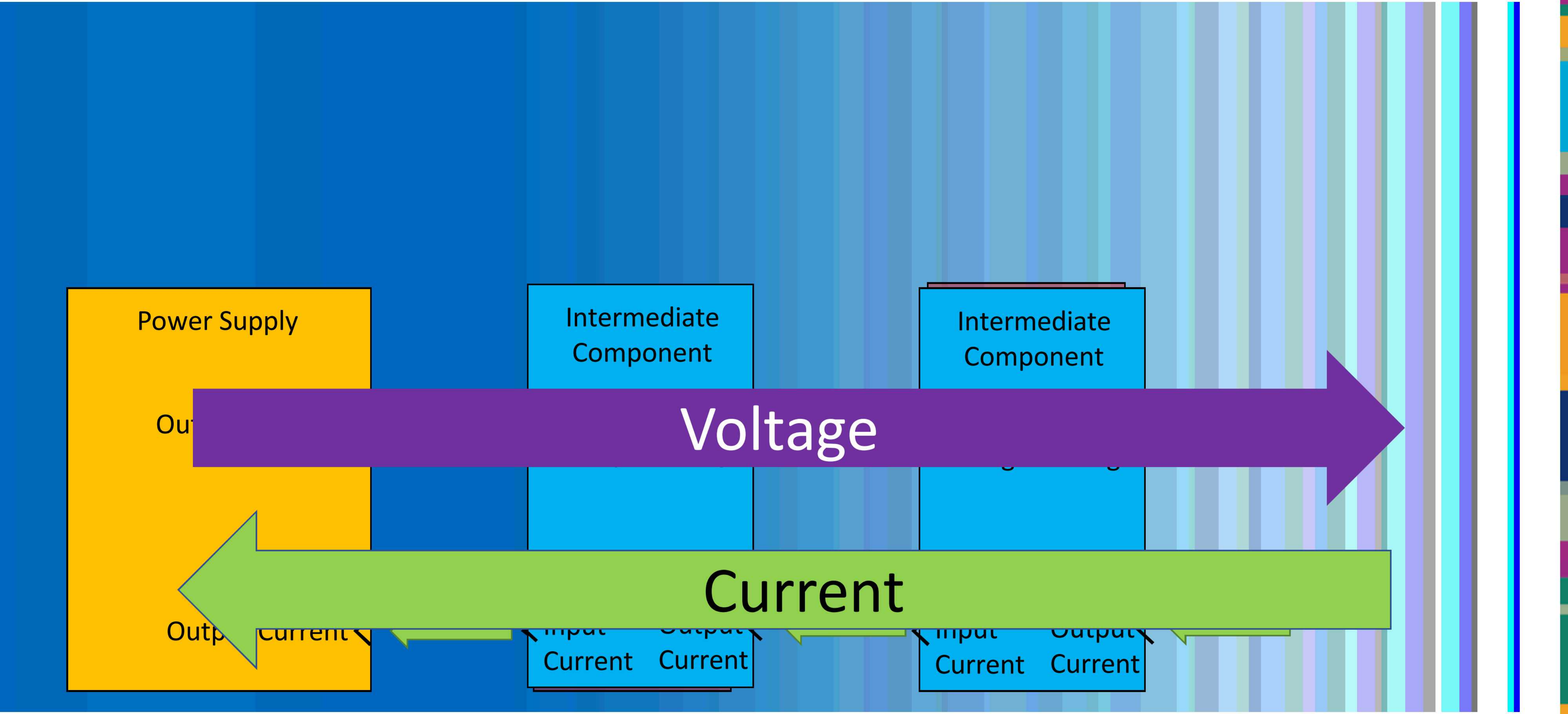
Can be added to existing linear models

User-Defined, Custom models can be made

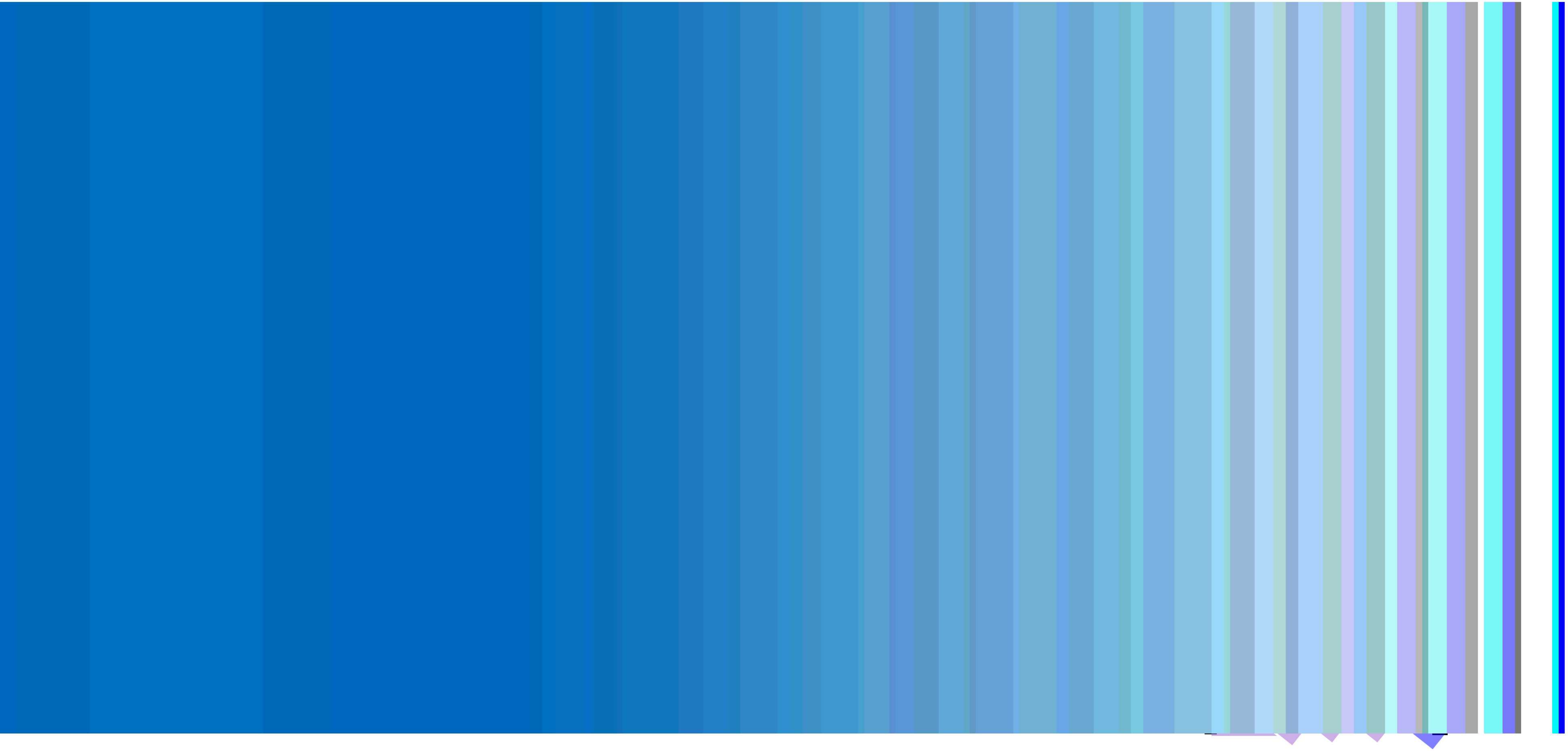
Electrical Modeling

- Analog
- Digital
- Power
  - Electrical - Thermal

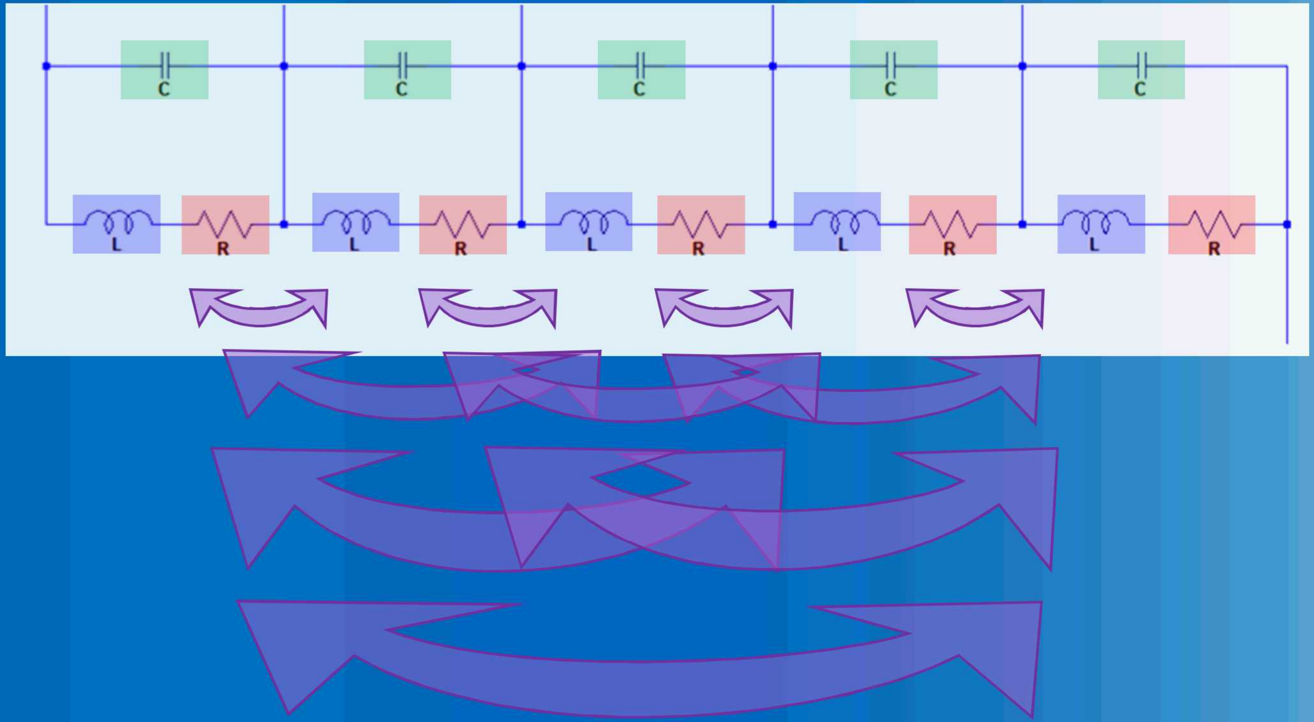
Electrical Modeling



Capacitive Networks



Inductive Networks



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

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

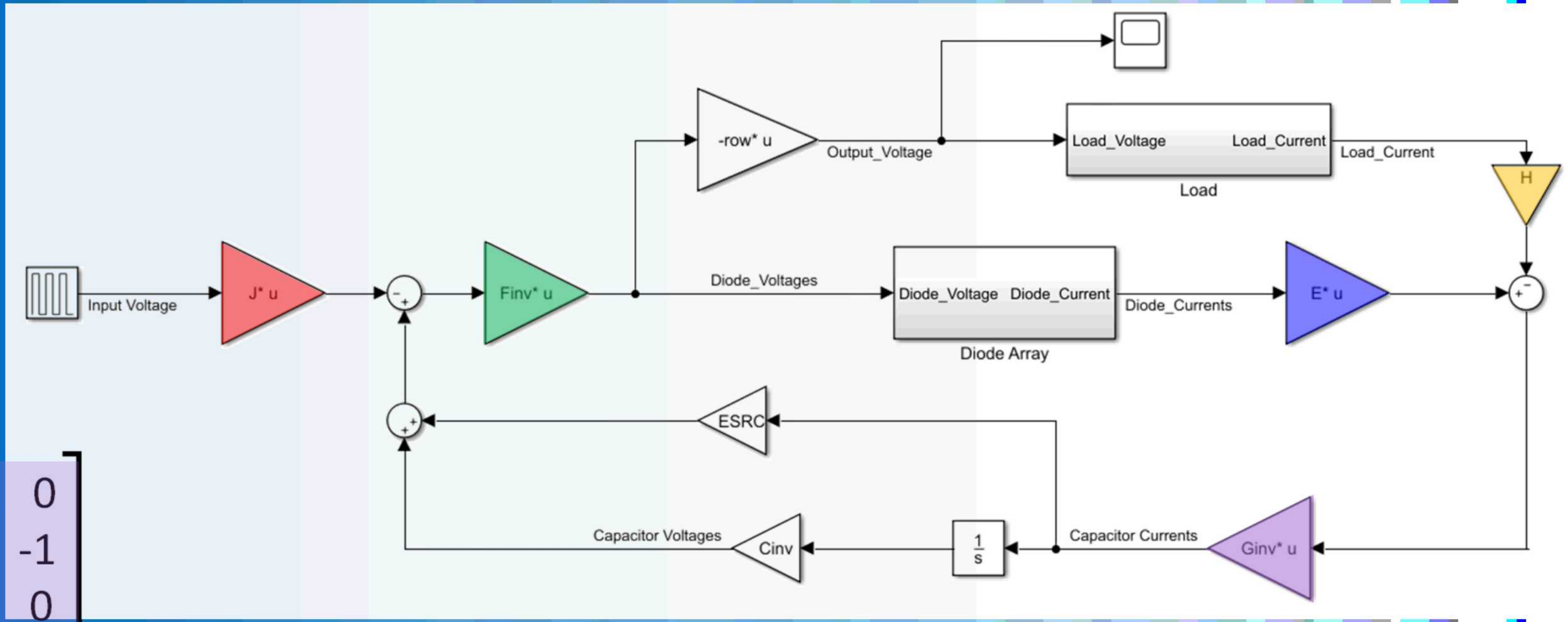
$$\begin{bmatrix} L_{11} & L_{12} & L_{13} & L_{14} & L_{15} \\ L_{21} & L_{22} & L_{23} & L_{24} & L_{25} \\ L_{31} & L_{32} & L_{33} & L_{34} & L_{35} \\ L_{41} & L_{42} & L_{43} & L_{44} & L_{45} \\ L_{51} & L_{52} & L_{53} & L_{54} & L_{55} \end{bmatrix}$$

Topologically Derived Charge Pump Constants

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

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

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

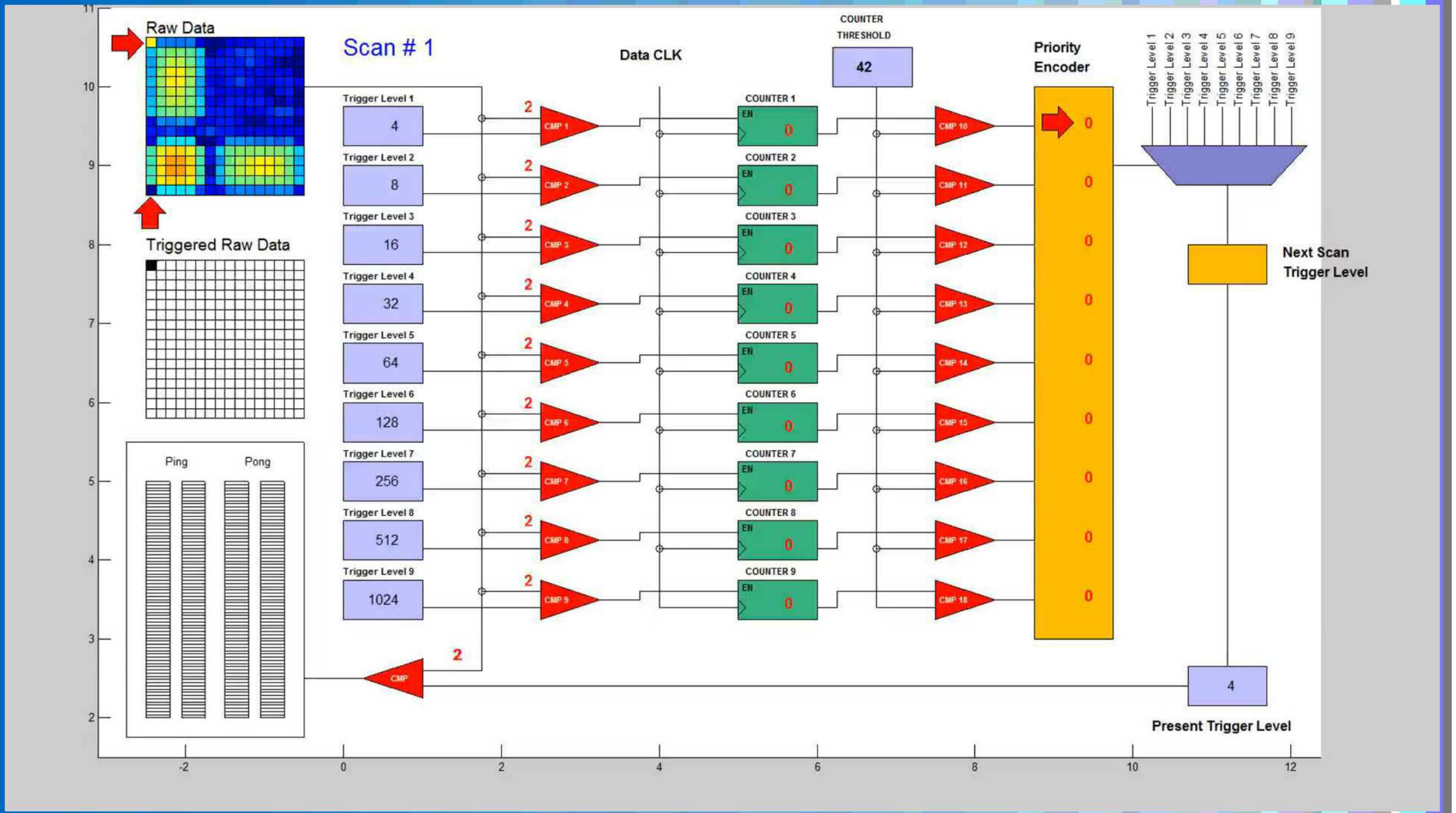


Electrical Modeling – Digital FPA Model Example

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)

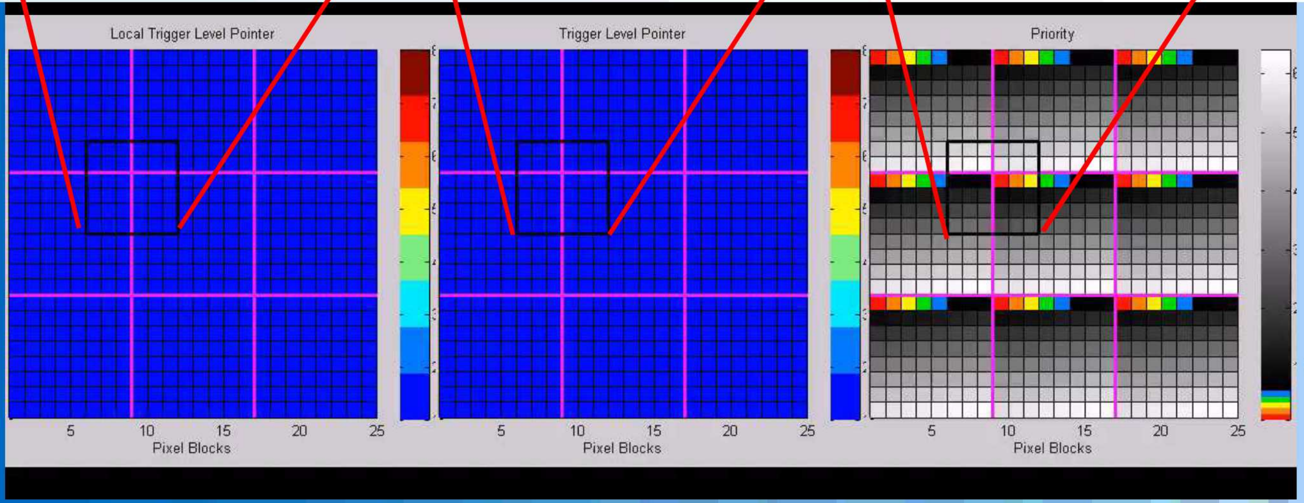


[Click on Video]

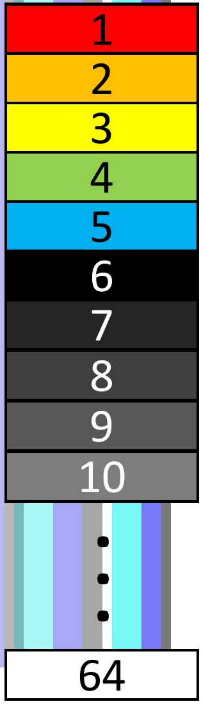
Electrical Modeling - Digital

384 x 384 Pixels,
2304 Digital Signal Processors

Entire Focal Plane array
1536 x 1536 Pixels

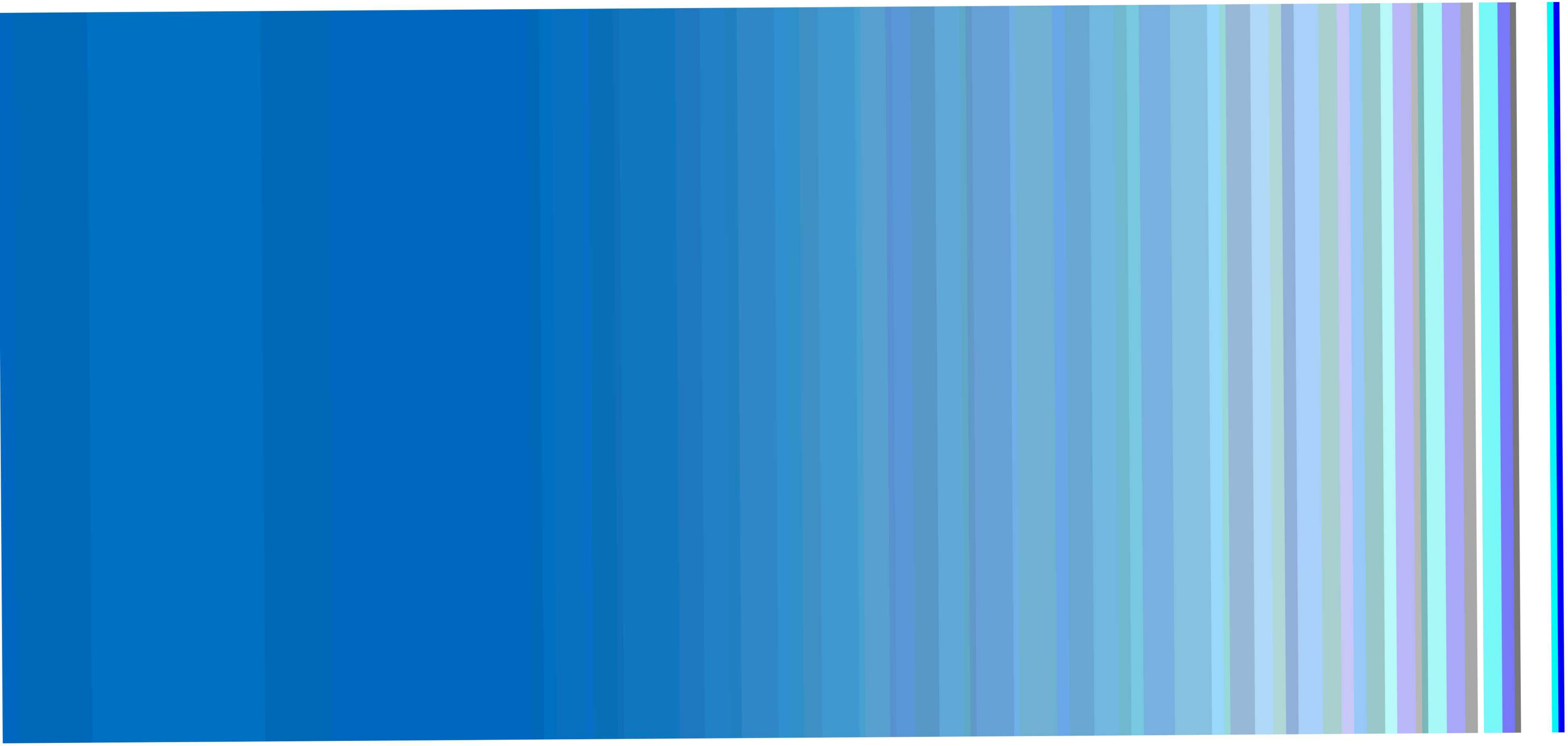


Top 5 Prioritized DSPs



[Click on Video]

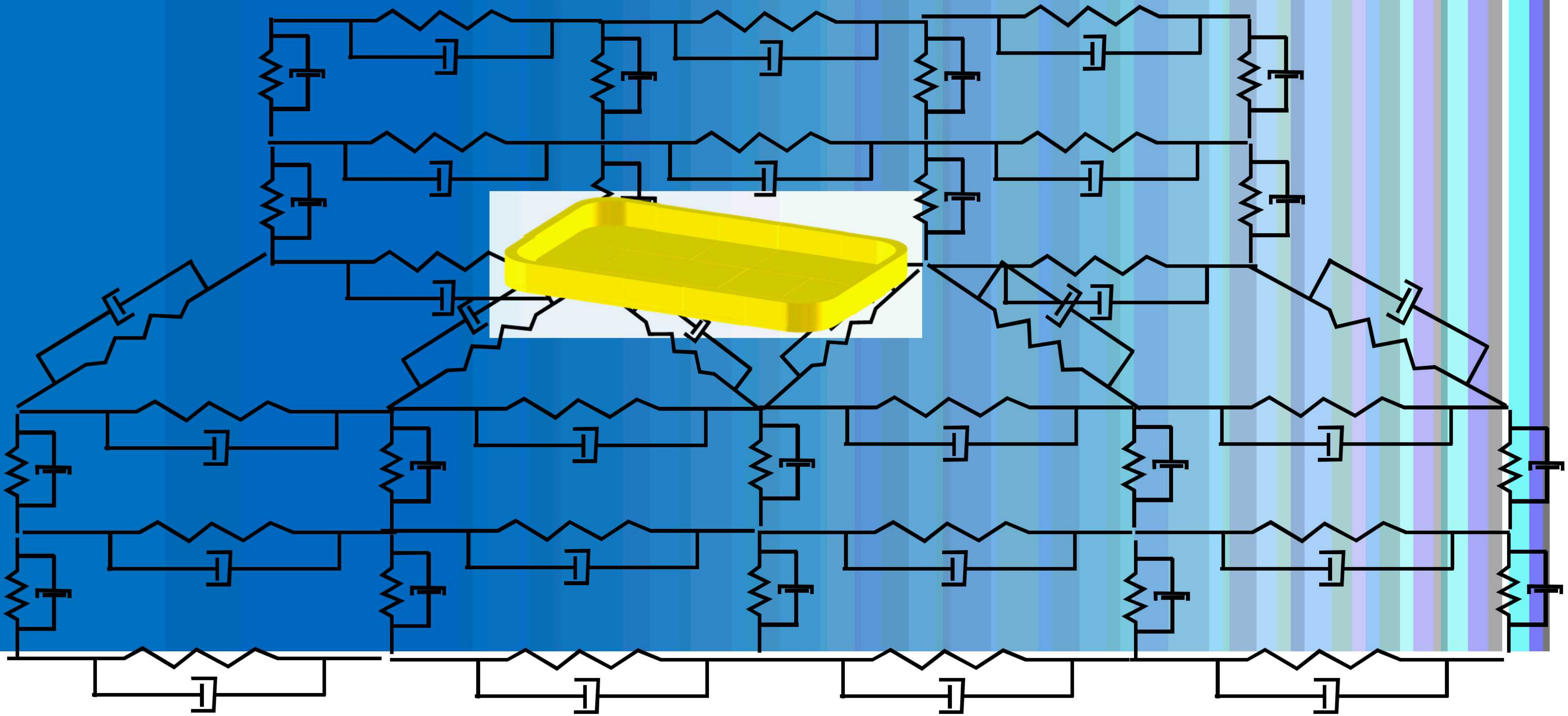
Electrical Conduction



Mechanical

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

Lumped Mass Reduced Order Modeling



Coupling Elements as Tensors vs Constants

Displacement / “Stretching”

Force

Stiffness Tensor

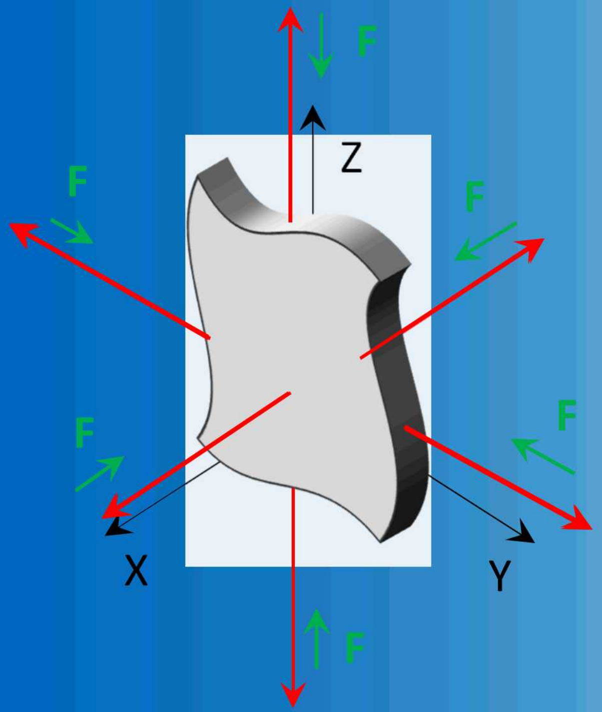
$$\begin{bmatrix} k_{xx23} & k_{xy23} & k_{xz23} \\ k_{yx23} & k_{yy23} & k_{yz23} \\ k_{zx23} & k_{zy23} & k_{zz23} \end{bmatrix}$$

Symmetry

Damping Tensor

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

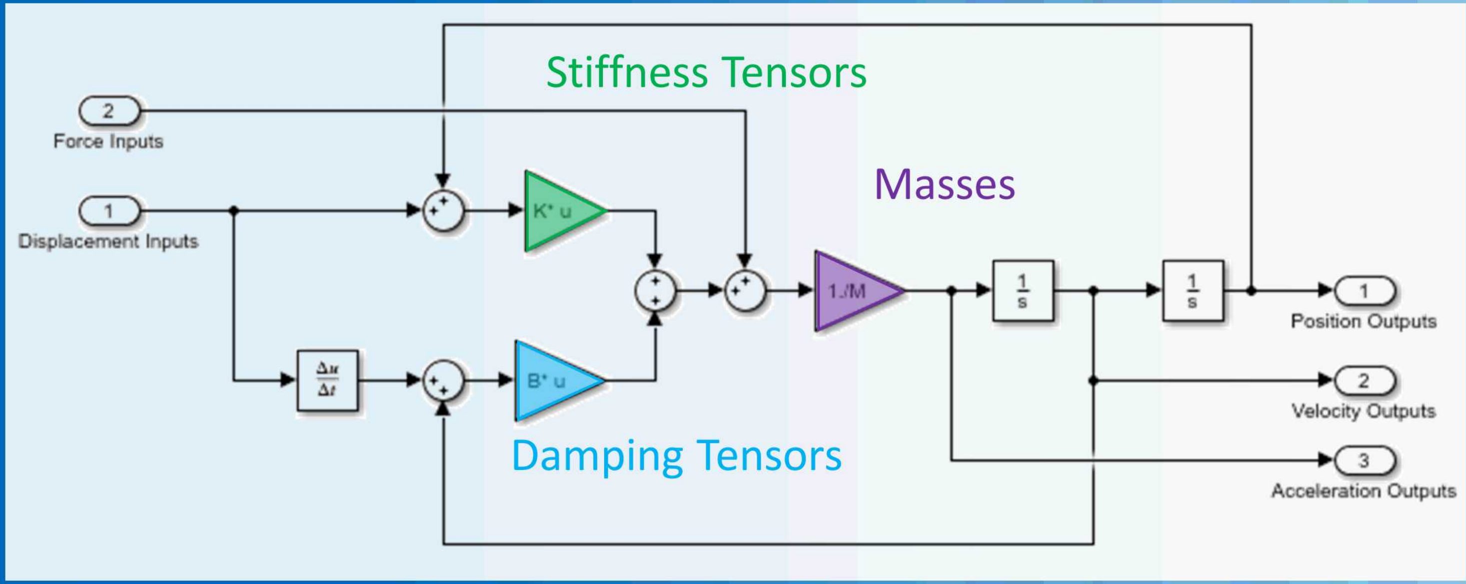
Symmetry



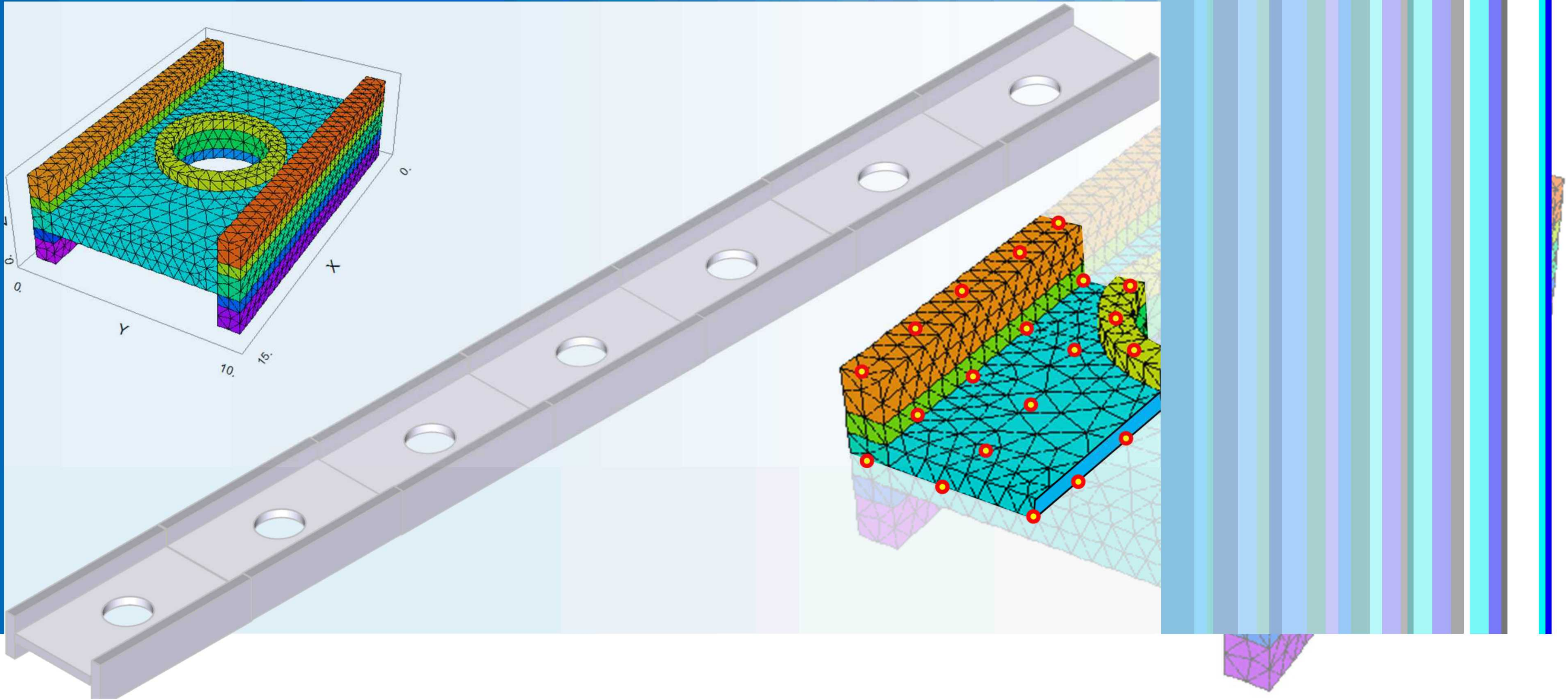
Stiffness Tensors in System Matrix

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}

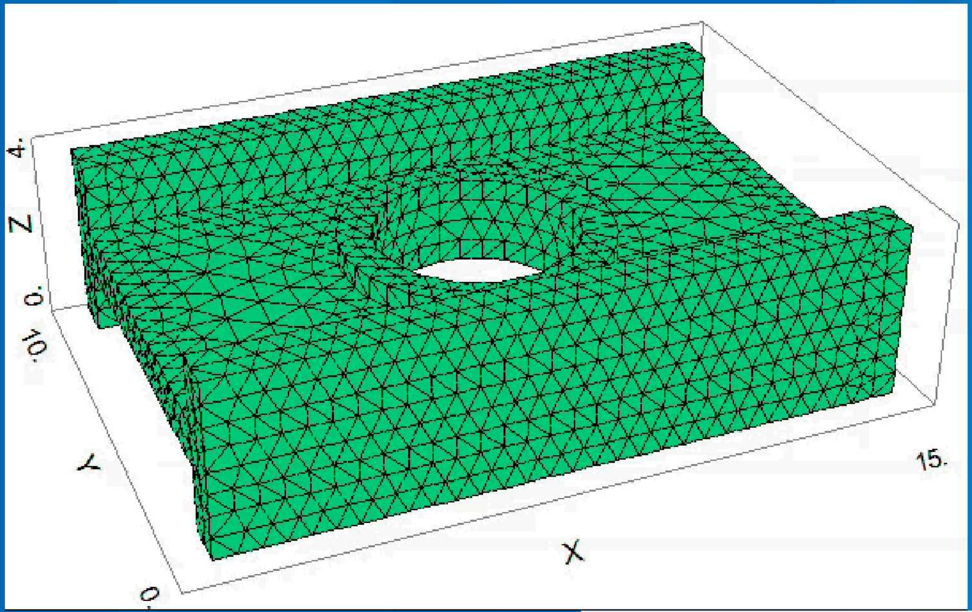
Modeling Mechanical Vibrations and Thermal Conduction in Simulink



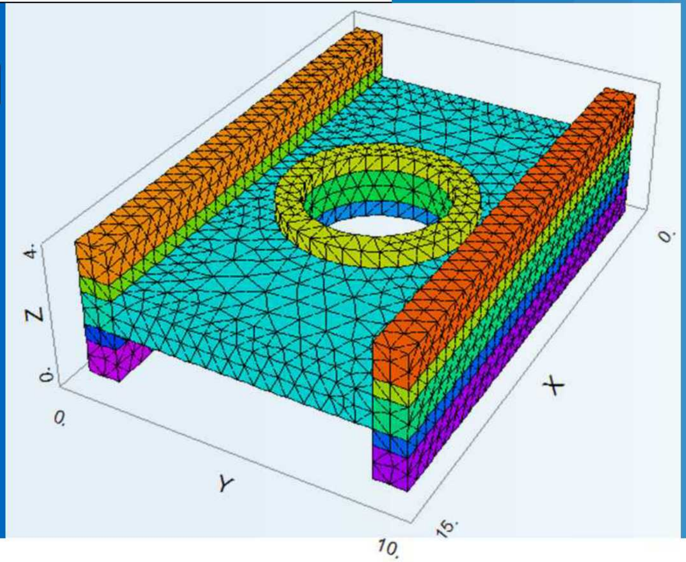
Vibration Example – Shell



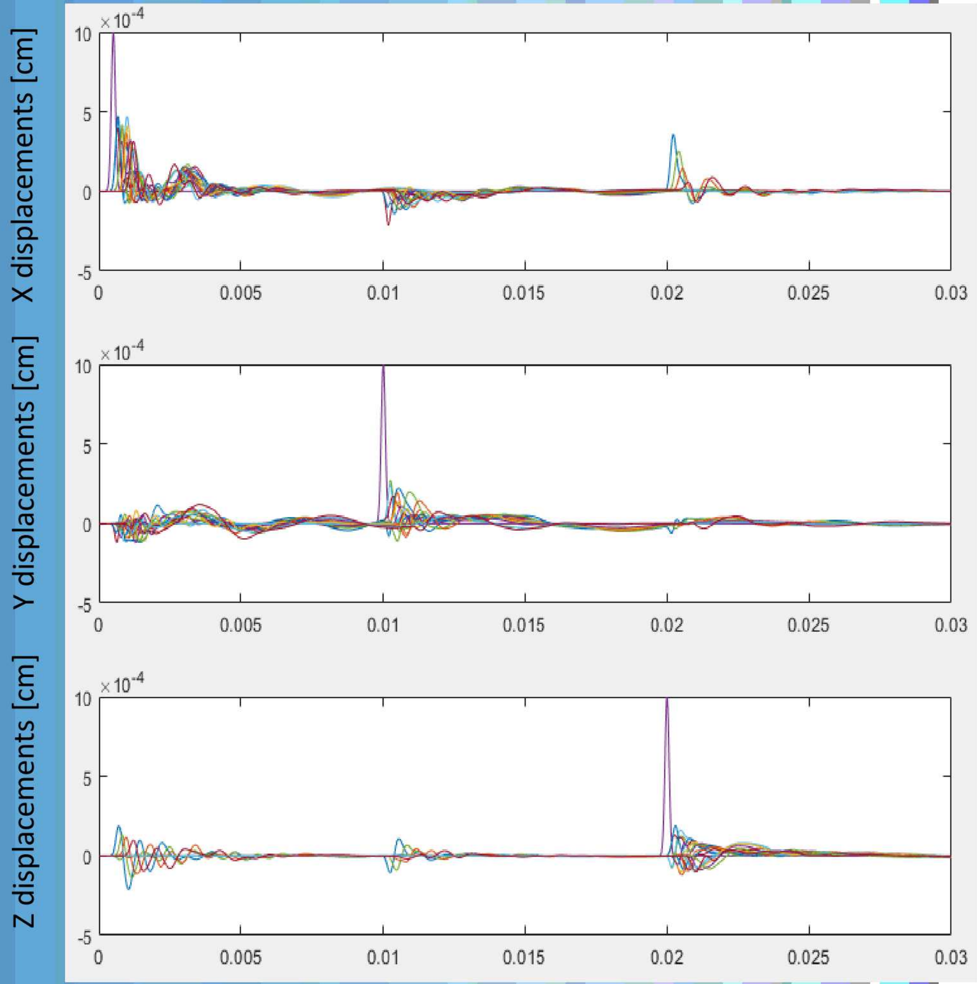
Vibration Example – Beam



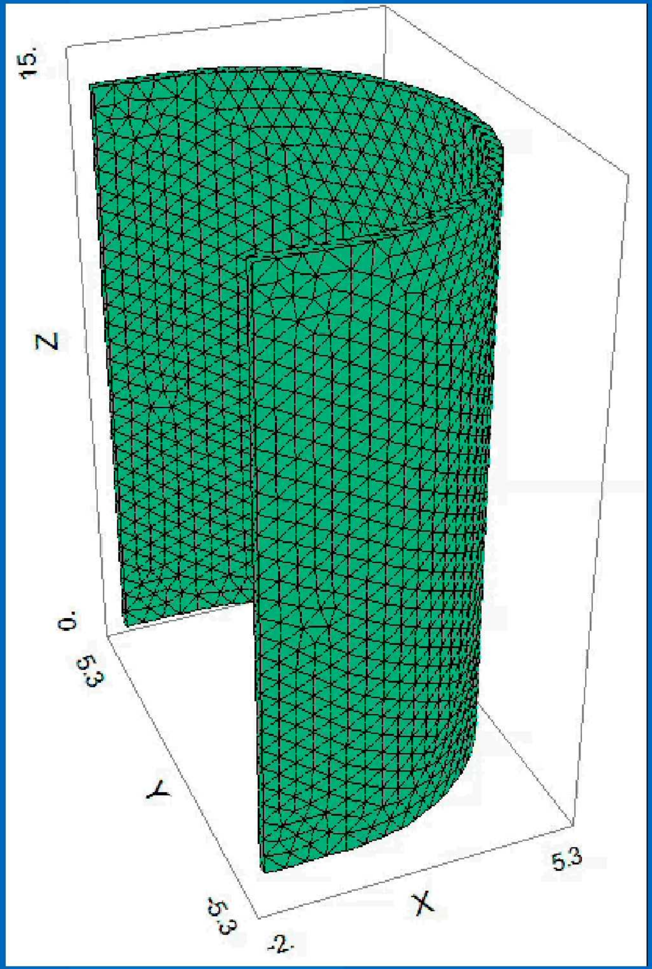
[Click on Video]



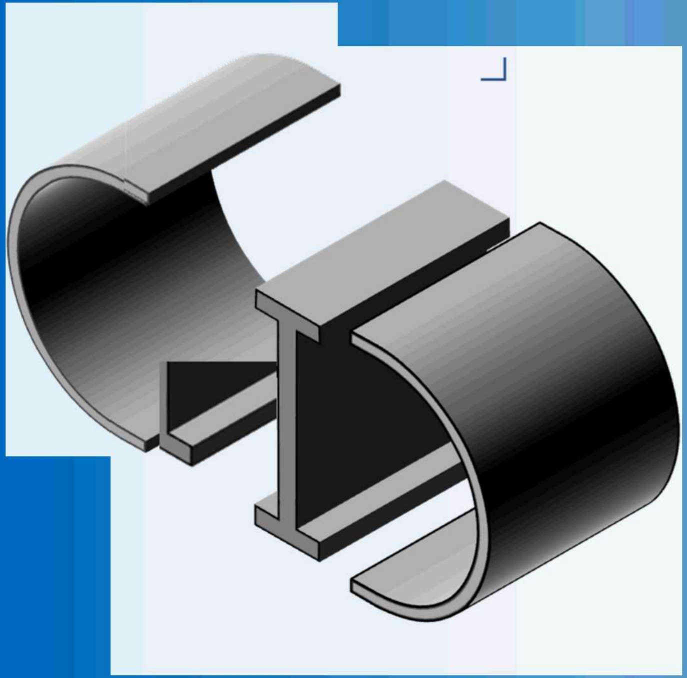
Displacements



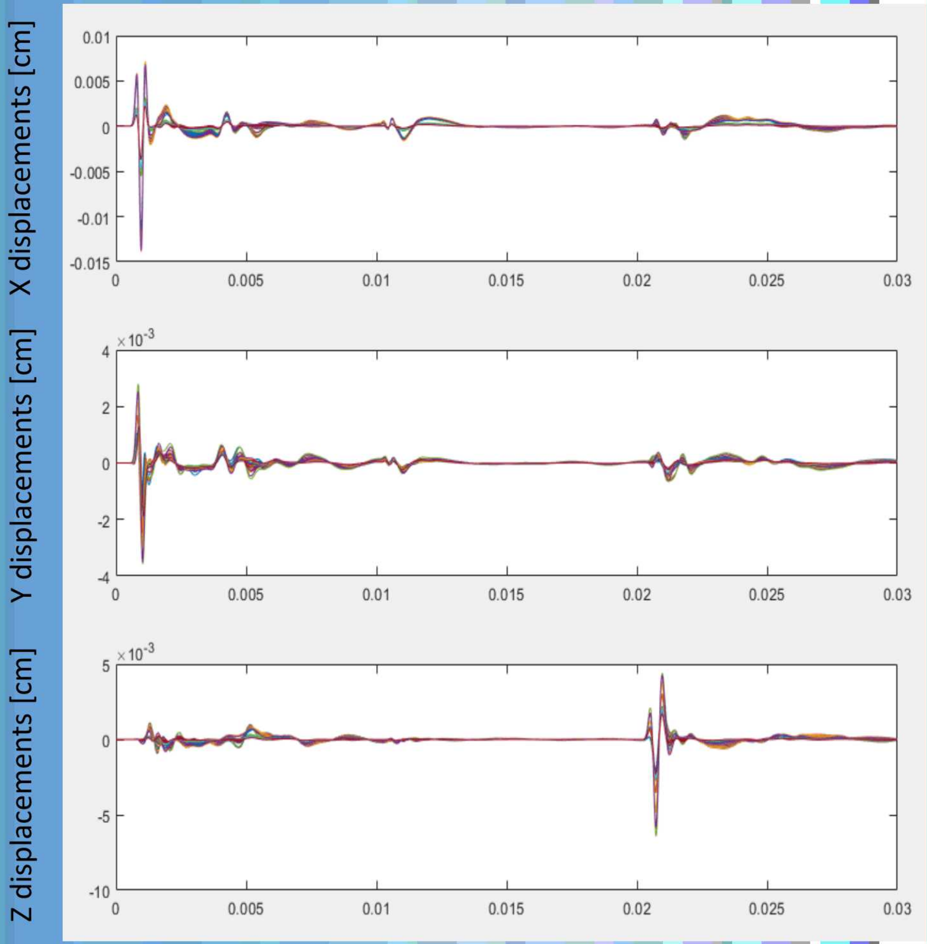
Vibration Example – Shell



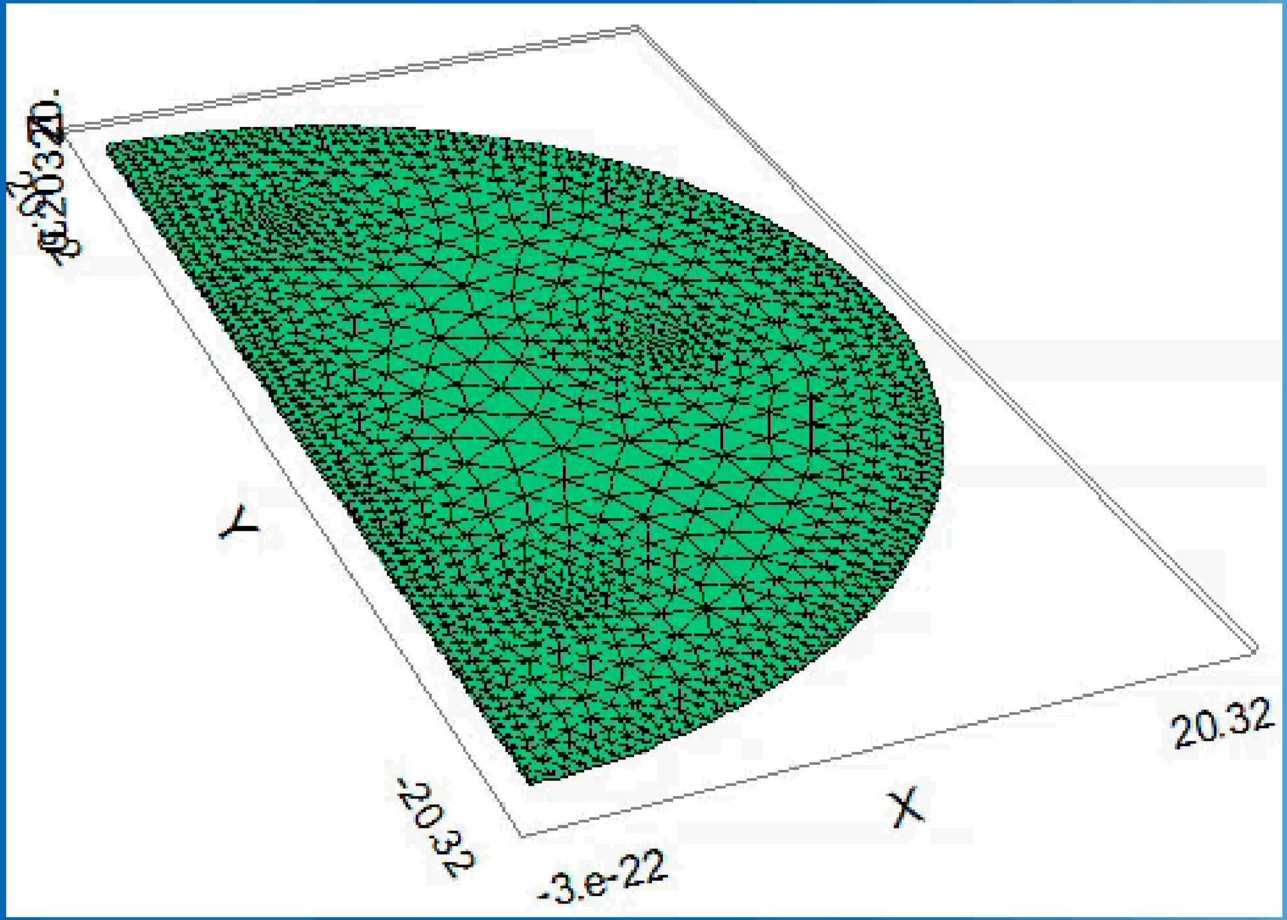
[Click on Video]



Displacements

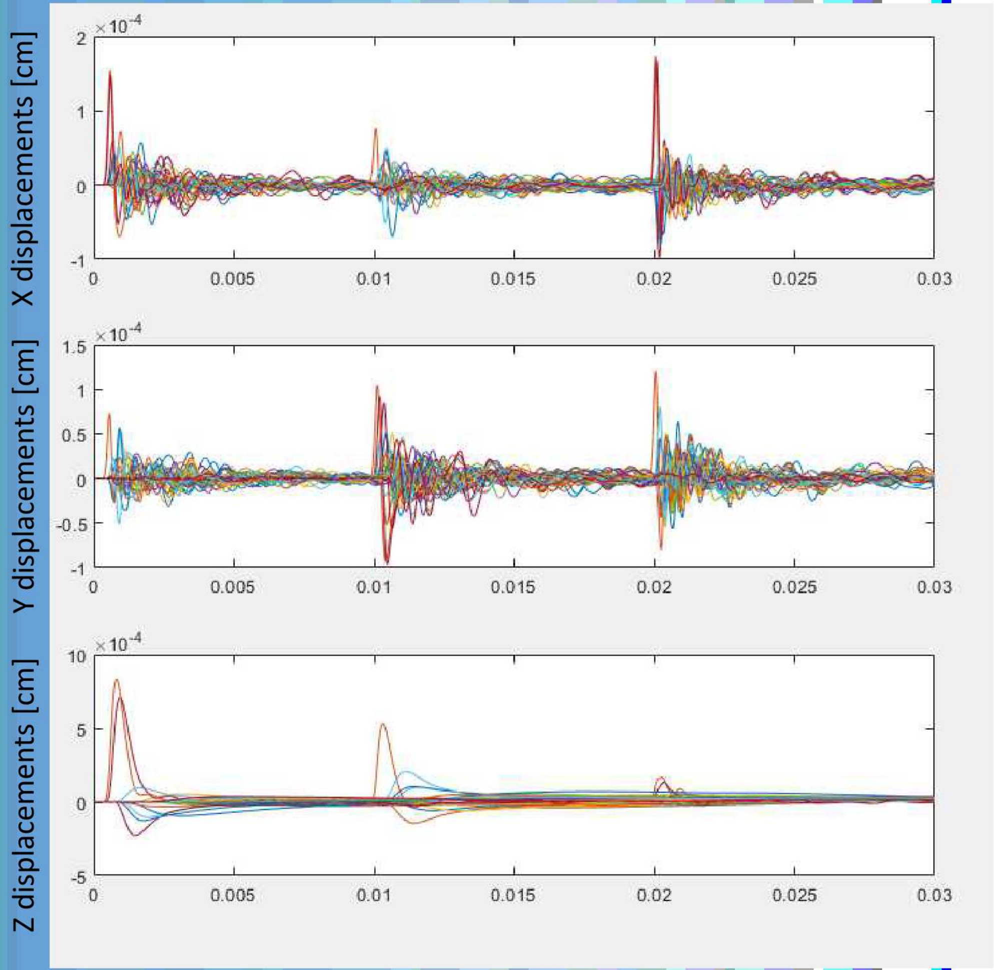


Vibration Example – Circuit Board



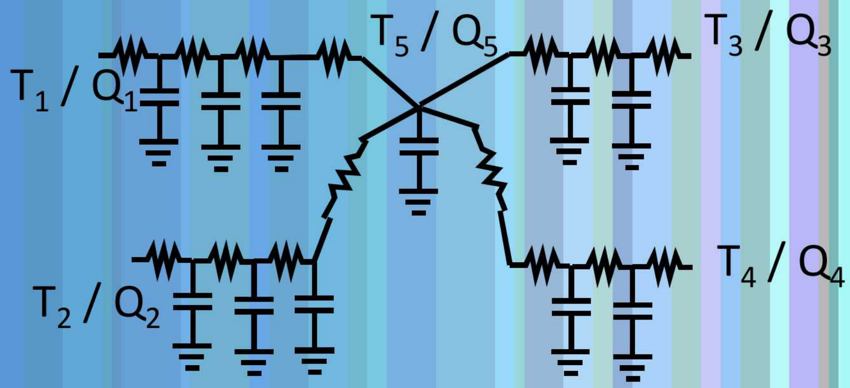
[Click on Video]

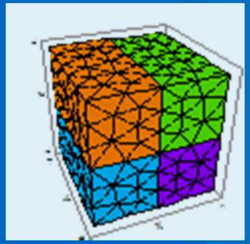
Displacements

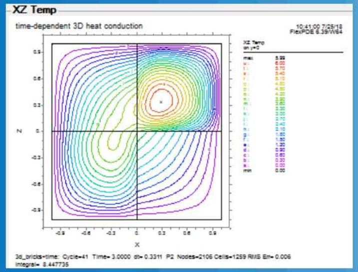


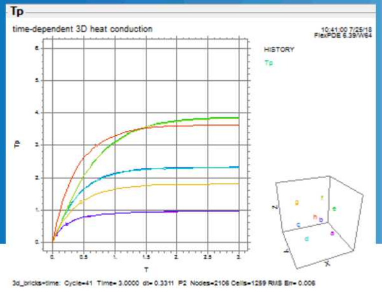
Thermal Modeling

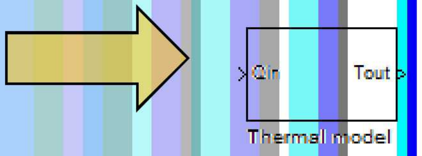
- Conduction
  - Thermal Resistance
  - Thermal Capacitance
- Convection
  - Free
  - Forced
- Radiation







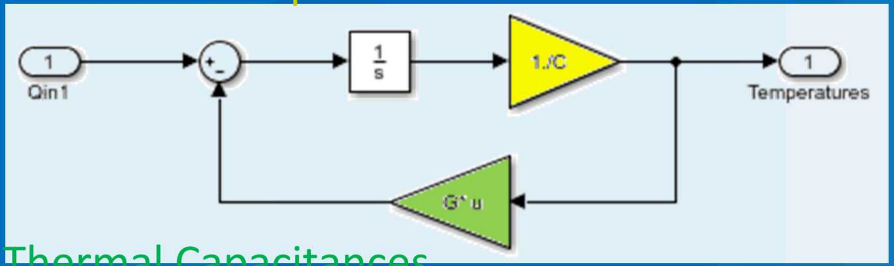




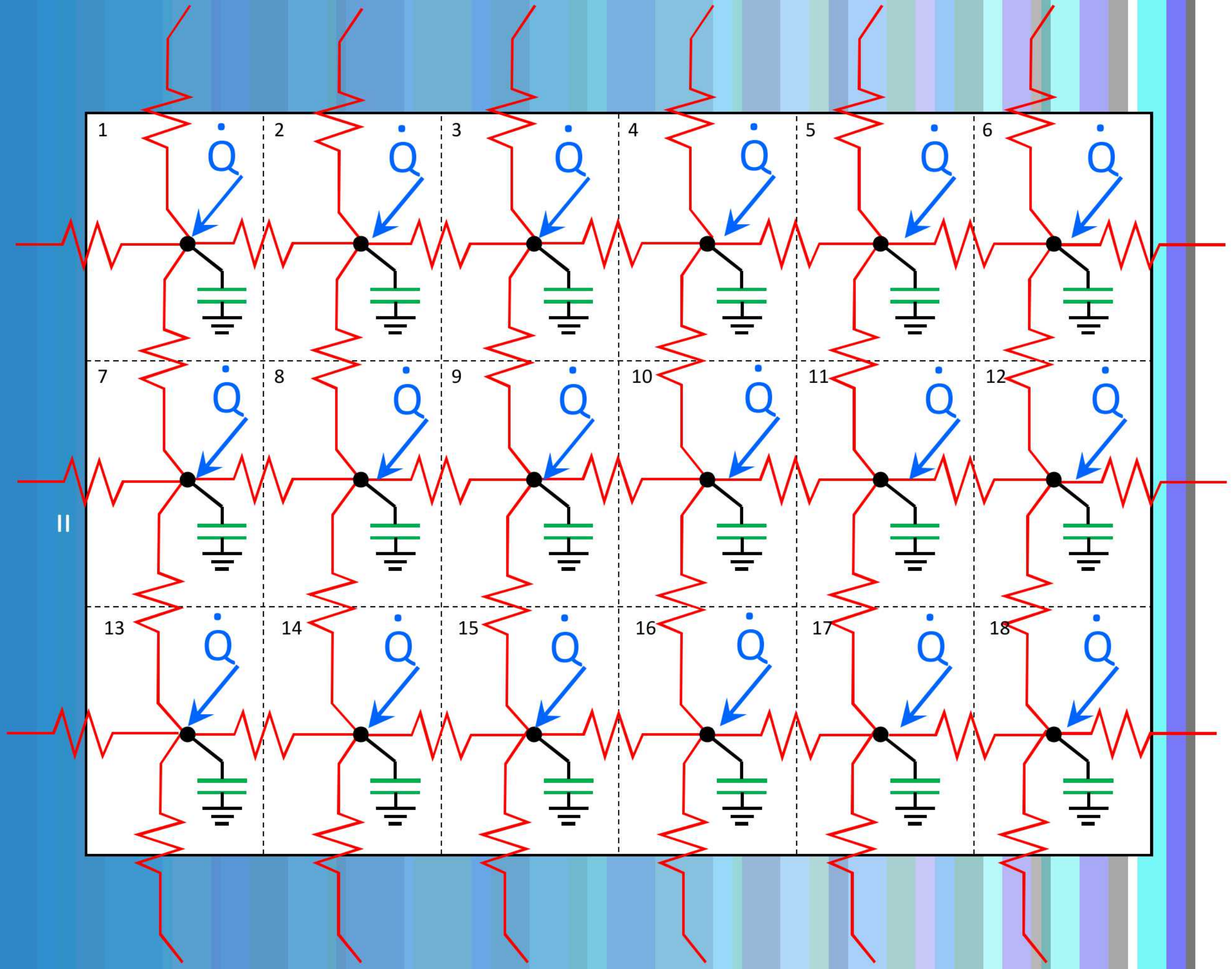
Thermal Modeling - Conduction

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

Thermal Capacitances



Thermal Capacitances



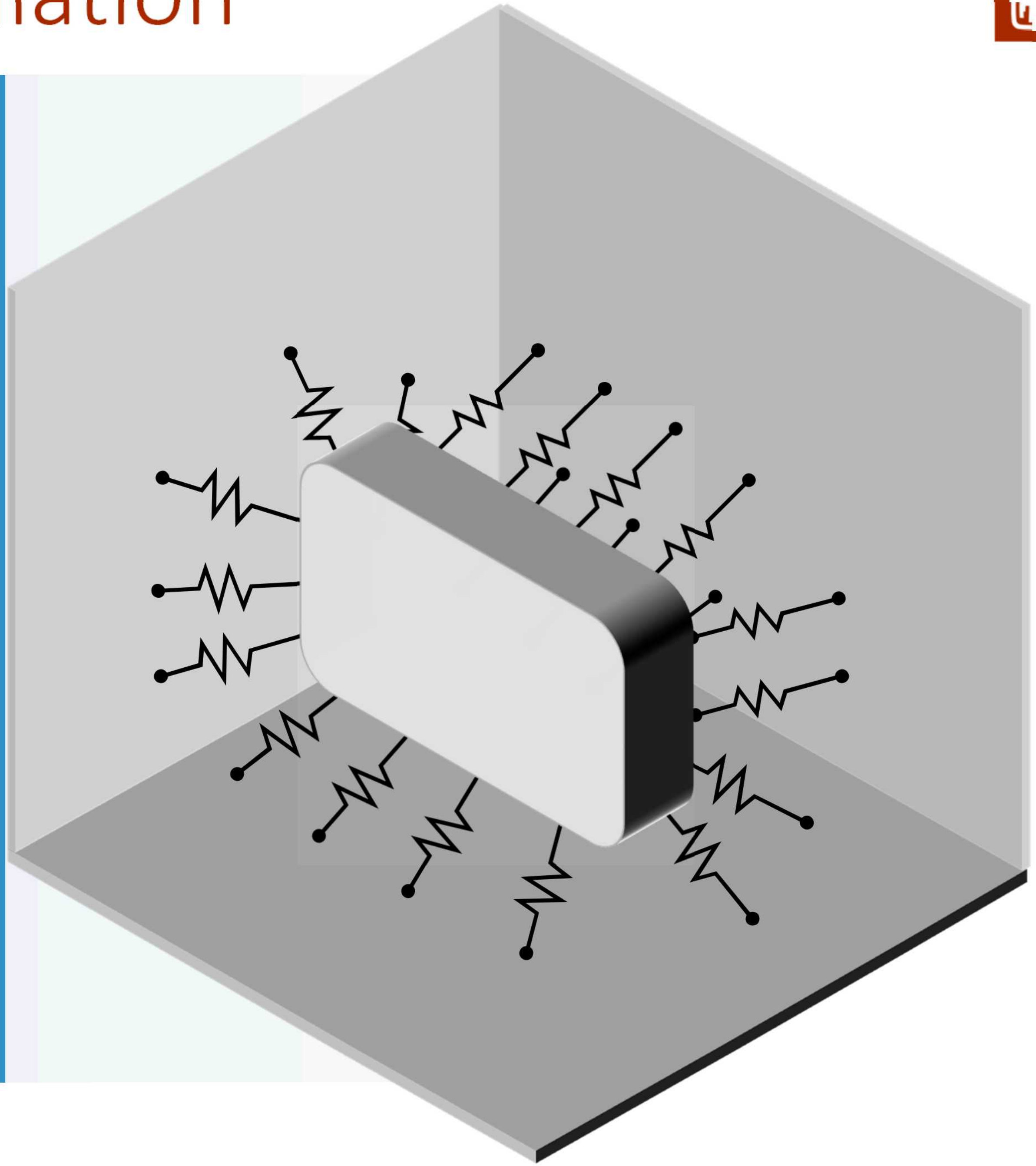
Thermal Modeling – Conduction Matrix

$$
[G] = \left[\begin{array}{cccccccccccccccccc}
-\Sigma\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{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\text{row}
\end{array}\right]
$$

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

G

Electro-Magnetic Fields

Radiated EMI (Power Converters)
Radar
Other..

Backup Slides

Extraction of Parameters

Four Element Example in 1D

$\underline{M_1}$

$$(k_{01}+sb_{01})(x_0-x_1) + (k_{21}+sb_{21})(x_2-x_1) + (k_{31}+sb_{31})(x_3-x_1) + (k_{41}+sb_{41})(x_4-x_1) = M_1s^2x_1$$

$\underline{M_2}$

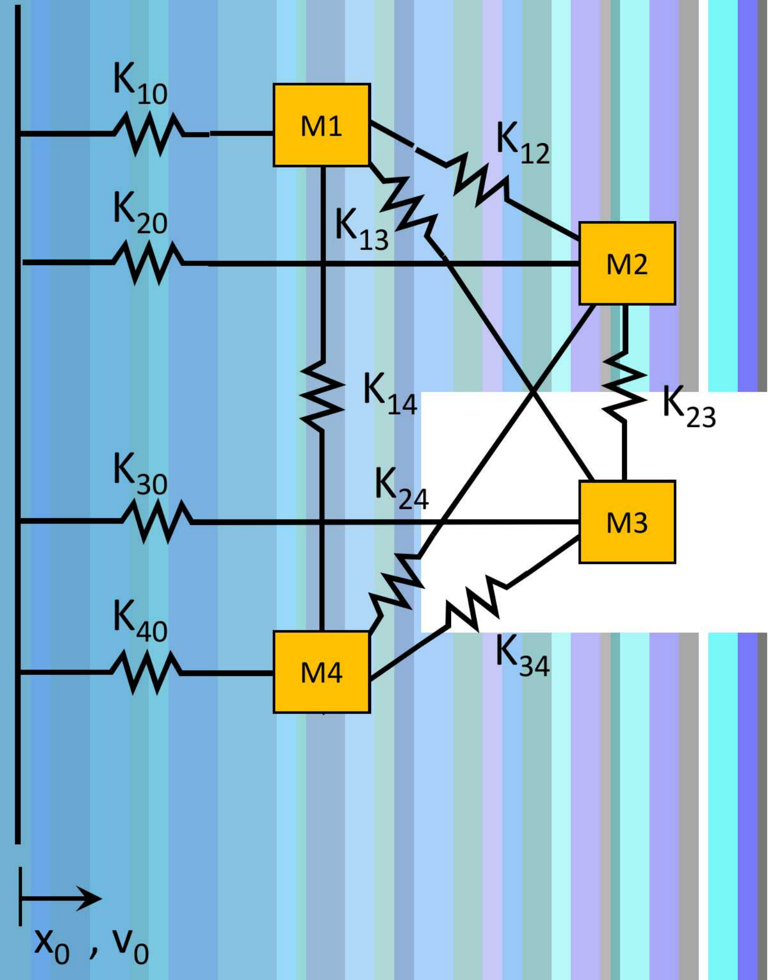
$$(k_{02}+sb_{02})(x_0-x_2) + (k_{21}+sb_{21})(x_1-x_2) + (k_{32}+sb_{32})(x_3-x_2) + (k_{42}+sb_{42})(x_4-x_2) = M_2s^2x_2$$

$\underline{M_3}$

$$(k_{03}+sb_{03})(x_0-x_3) + (k_{13}+sb_{13})(x_1-x_3) + (k_{23}+sb_{23})(x_2-x_3) + (k_{43}+sb_{43})(x_4-x_3) = M_3s^2x_3$$

$\underline{M_4}$

$$(k_{04}+sb_{04})(x_0-x_4) + (k_{14}+sb_{14})(x_1-x_4) + (k_{24}+sb_{24})(x_2-x_4) + (k_{34}+sb_{34})(x_3-x_4) = M_4s^2x_4$$



Multivariable Regression

$\underline{M_1}$

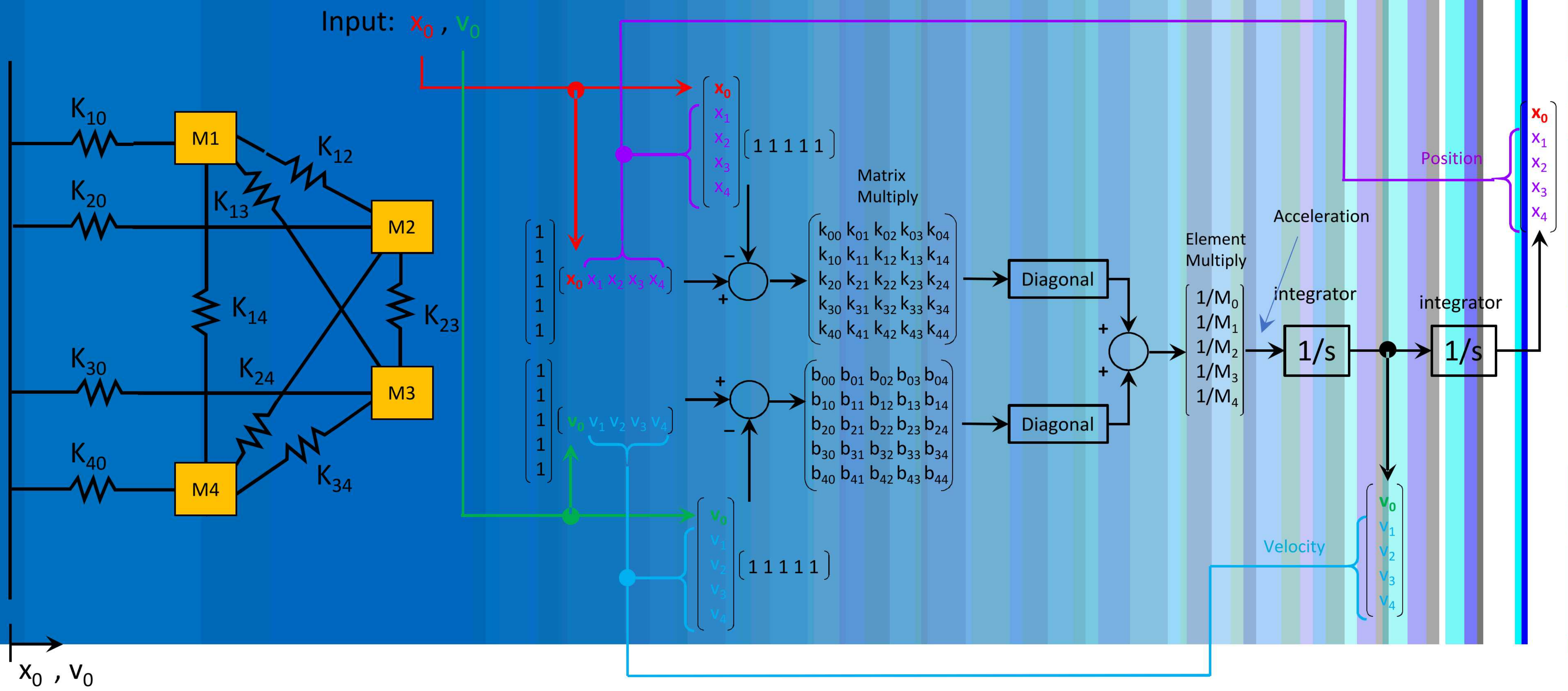
$$\frac{k_{01}}{M_1}(x_0-x_1) + \frac{b_{01}}{M_1}(v_0-v_1) + \frac{k_{21}}{M_1}(x_2-x_1) + \frac{b_{21}}{M_1}(v_2-v_1) + \frac{k_{31}}{M_1}(x_3-x_1) + \frac{b_{31}}{M_1}(v_3-v_1) + \frac{k_{41}}{M_1}(x_4-x_1) + \frac{b_{41}}{M_1}(v_4-v_1) = a_1$$

Known

Unknown

Solve for Unknowns → Extract Stiffness and Damping tensor components

4 Element System in 1D



Full System Model Simulation Indicates when