COMSOL Day

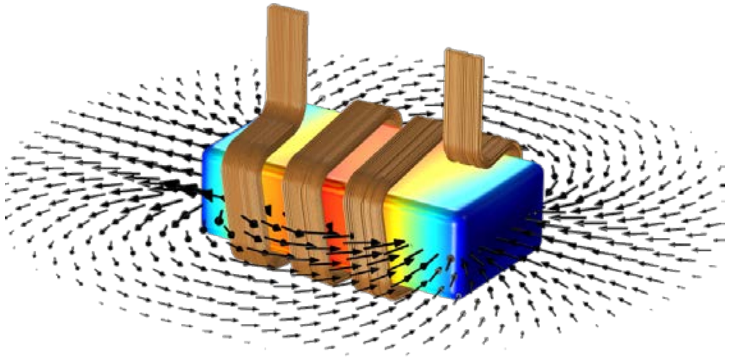
Orange County

Thursday

May 17, 2018

8:30AM–4:00PM

Low-Frequency Electromagnetics with COMSOL Multiphysics®

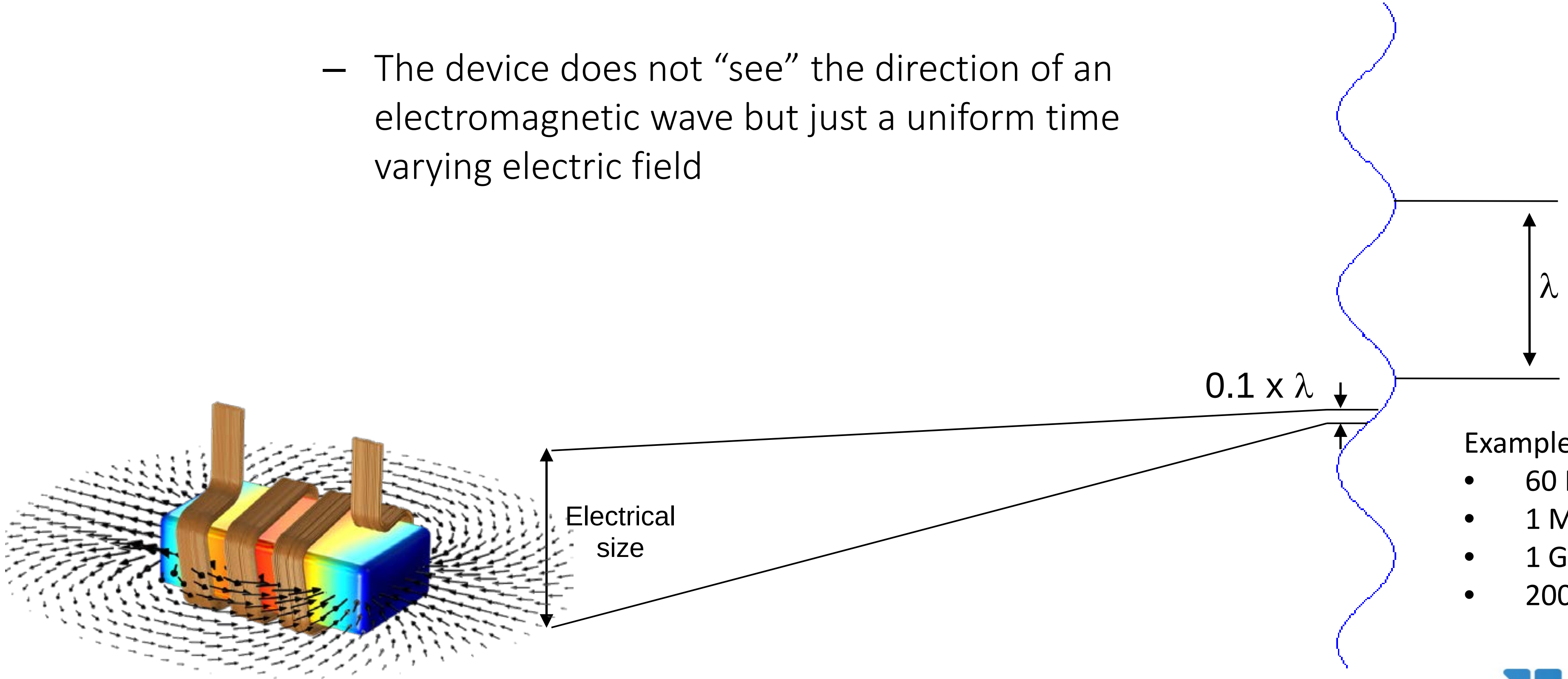


Ping Chu

Los Angeles, COMSOL, Inc.

Low Frequency or High Frequency?

- What is low frequency?
  - The device does not “see” the direction of an electromagnetic wave but just a uniform time varying electric field



Examples of wavelengths in air

• 60 Hz	5000 km
• 1 MHz	300 m
• 1 GHz	30 cm
• 200 THz	1.5 µm

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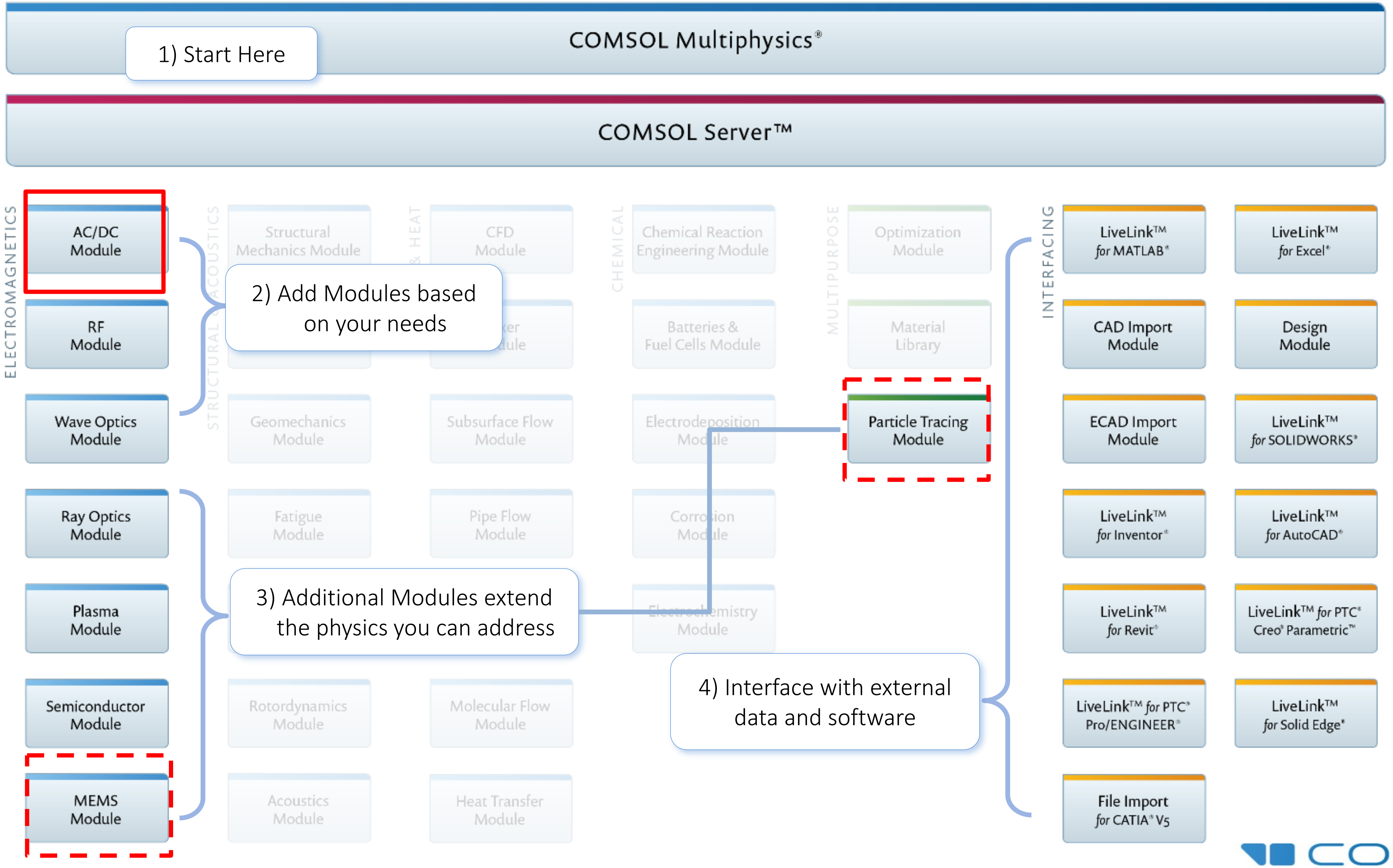
Electromagnetics is Extended by Add-on Modules



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Built-in Physics Interfaces

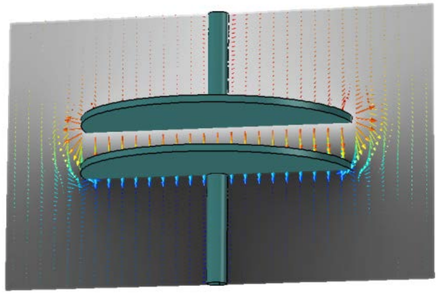
- AC/DC Module
  - *Electrostatics*[1], *Electrostatics BEM*
  - *Electric Currents*[1]
  - *Electric Currents – Shell*
  - *Electrical Circuit*
  - *Magnetic Fields, No Currents (FEM/BEM)*
  - *Magnetic Fields*[1]
  - *Magnetic and Electric Fields*
  - *Rotating Machinery, Magnetic*
  - *Magnetic Field Formulation*
  - *Joule Heating*[1,2]
  - *Induction Heating*[2]
  - *Magnetostriction*[2]

1 This physics interface is included with the core COMSOL Multiphysics® package but has added functionality for this module.

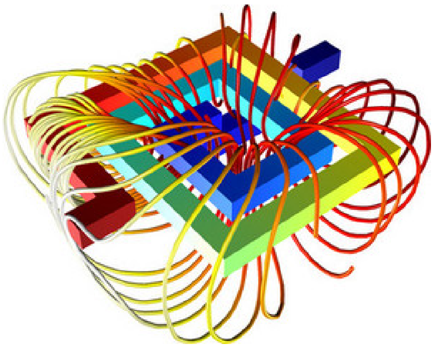
2 This physics interface is a predefined multiphysics coupling that automatically adds all of the physics interfaces and coupling features required.

https://www.comsol.com/products/specifications/

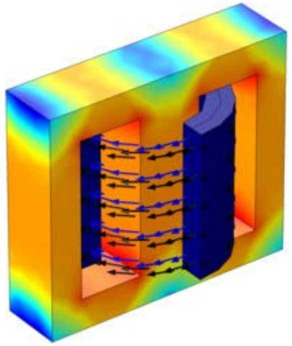
AC/DC Module Applications: (Static, Low Frequency, Some Transient)



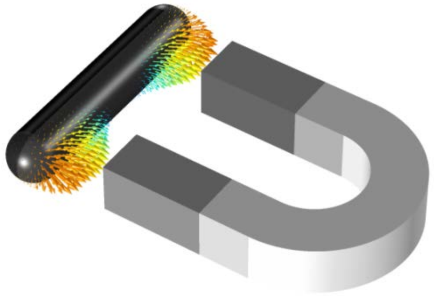
Resistive and Capacitive Devices (Including Touchscreens)



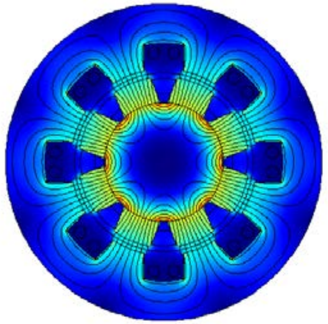
Inductors and Coils



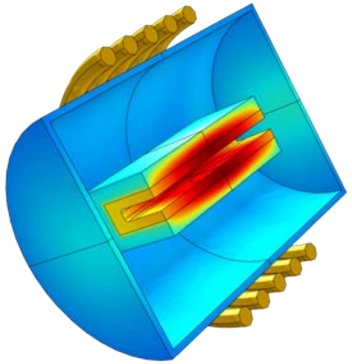
Nonlinear Magnetic Material



Magnets



Motors and Actuators



Multiphysics: Heating and Magnetostriction

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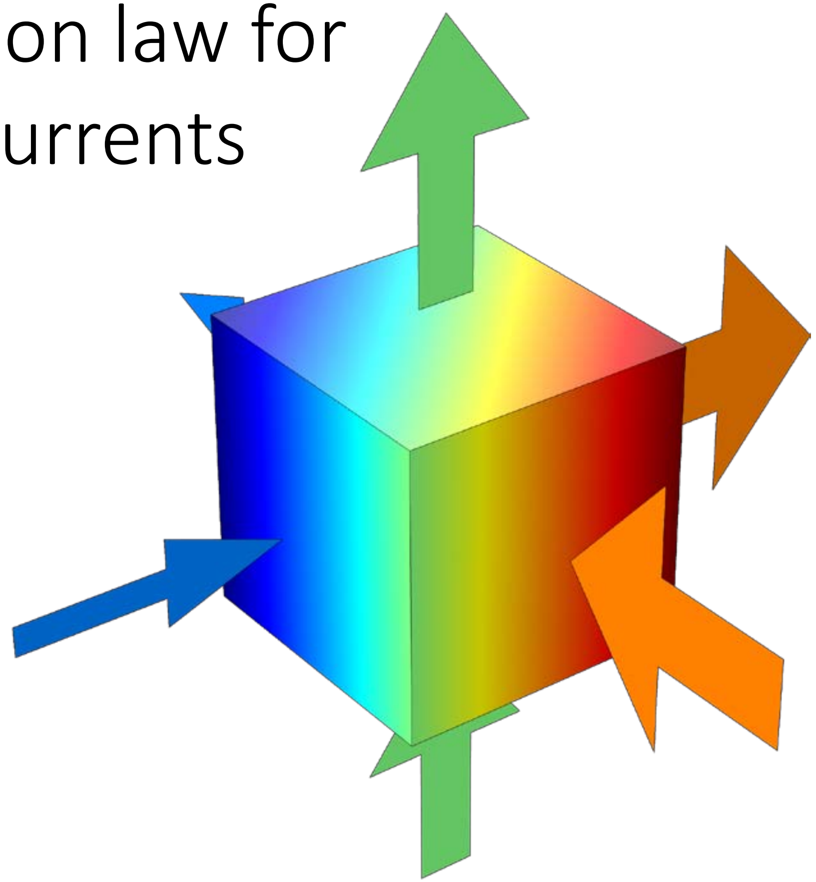
Poisson's Equation

- We get a conservation law for stationary electric currents
- Other examples:
  - Magnetostatics
  - Electrostatics
  - Heat transfer



$$-\nabla \cdot (\boldsymbol{\sigma} \nabla V) = Q_j$$

$$\nabla \cdot (\boldsymbol{\sigma} \boldsymbol{E}) = Q_j$$

$$\nabla \cdot \boldsymbol{J} = Q_j$$

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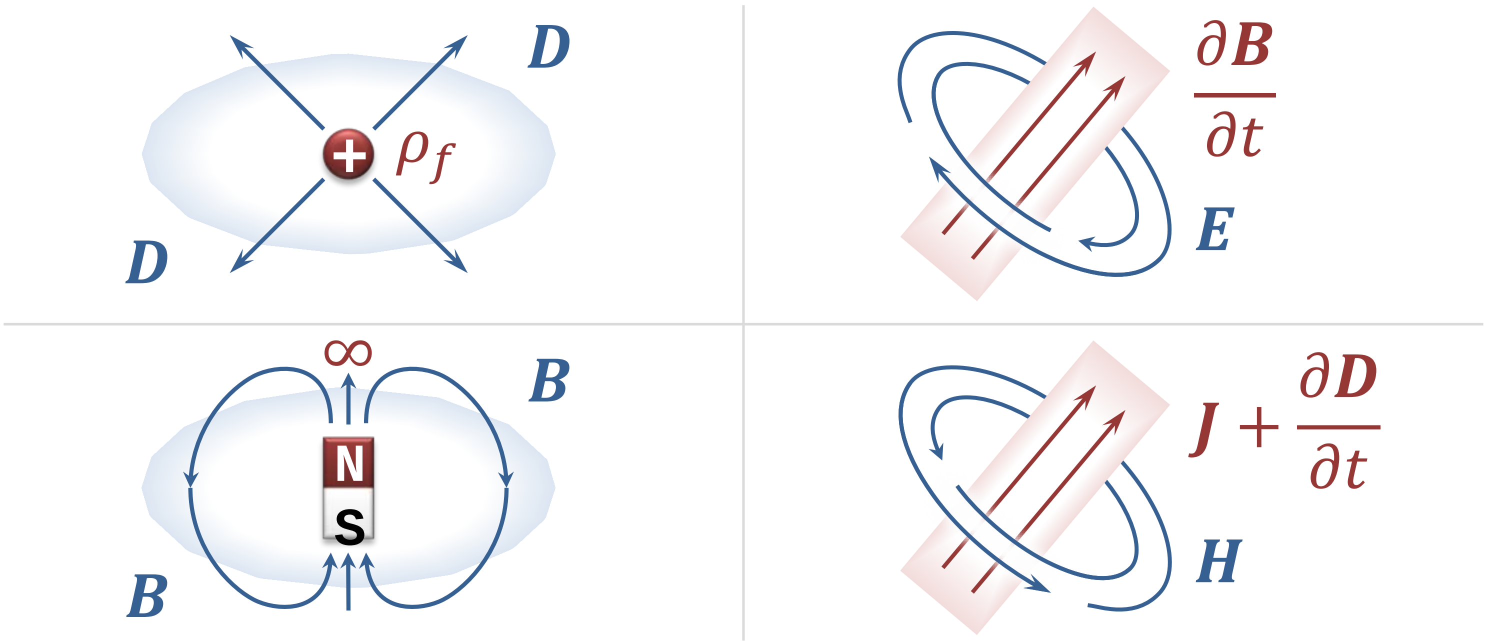
Maxwell’s Equations

Gauss	$\nabla \cdot \mathbf{D} = \rho$	$\nabla \times \mathbf{E} = 0 - \partial \mathbf{B}/\partial t - j\omega \mathbf{B}$	*Faraday’s law*
M-Gauss	$\nabla \cdot \mathbf{B} = 0$	$\nabla \times \mathbf{H} = 0 + \mathbf{J} + \partial \mathbf{D}/\partial t + j\omega \mathbf{D}$	*Maxwell-Ampère’s law*

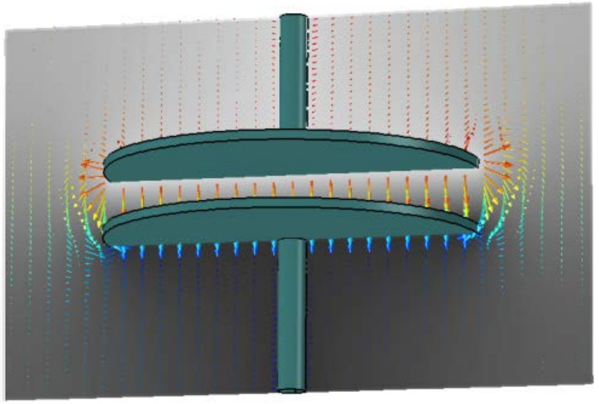


Resistive and Capacitive Devices Modelling

- AC/DC
  - Electric Currents (ec)
  - Electric Currents, Shell (ecs)
  - Electrical Circuit (cir)
  - Electrostatics (es)
  - Electrostatics, Boundary Elements (esbe)
  - Magnetic Field Formulation (mfh)
  - Magnetic Fields (mf)
  - Magnetic Fields, No Currents (mfnc)
  - Magnetic Fields, No Currents, Boundary Elements
  - Magnetic and Electric Fields (mef)
  - Rotating Machinery, Magnetic (rmm)

Resistive and capacitive

Electrostatic analysis (insulators)	Electrostatics + Stationary
DC resistive device (conductors)	Electric Currents + Stationary
AC resistive and AC capacitive devices	Electric Currents + Frequency Domain
Transient analysis	Electric Currents + Time Dependent



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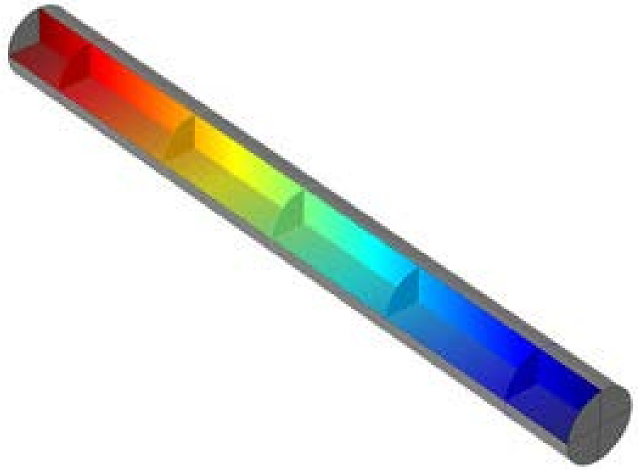

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Resistive and capacitive

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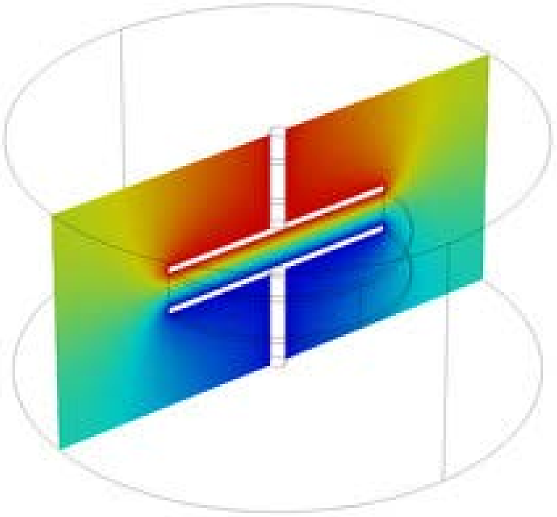
DC resistive device (conductors) → Electric Currents + Stationary

AC resistive and AC capacitive devices → Electric Currents + Frequency Domain

Transient analysis → Electric Currents + Time Dependent



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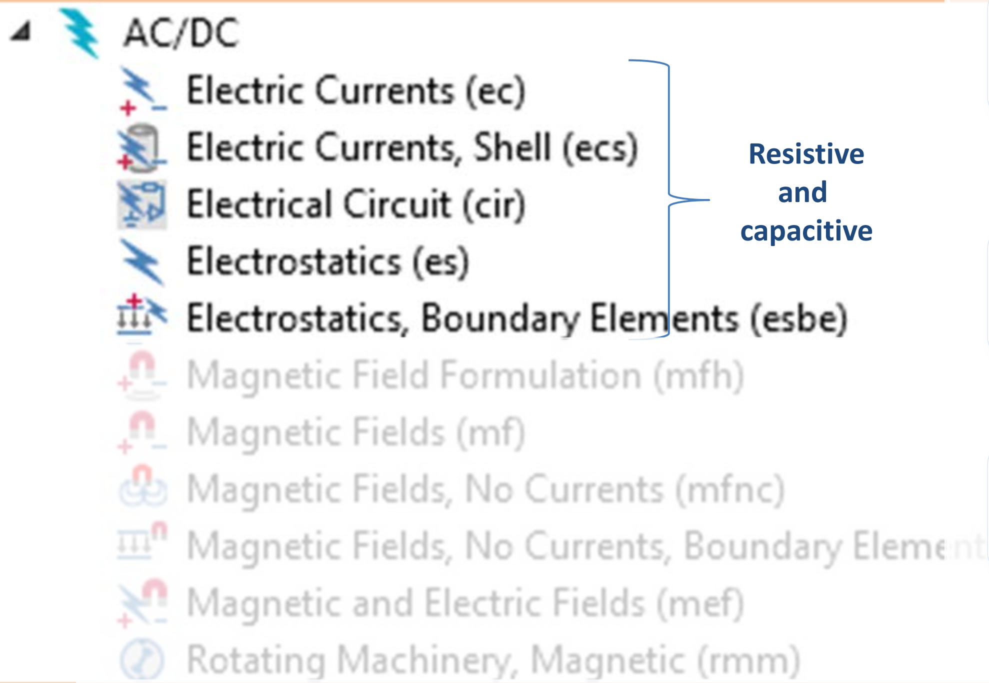
Resistive and Capacitive Devices Modelling



Resistive and capacitive

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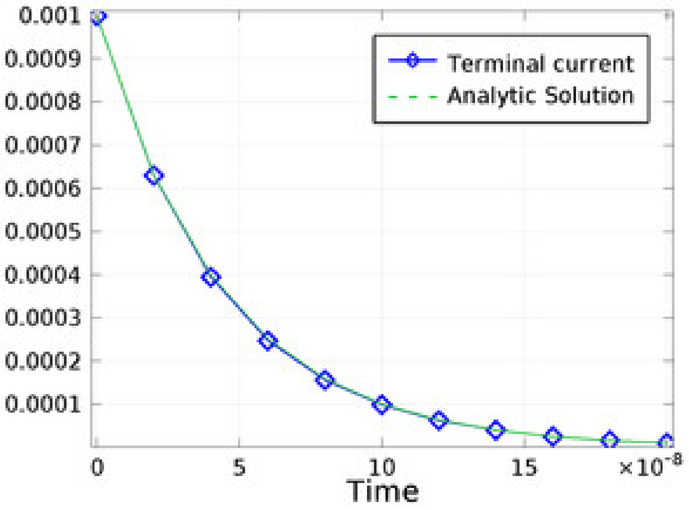

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Magnets, Coils and Motors Modelling

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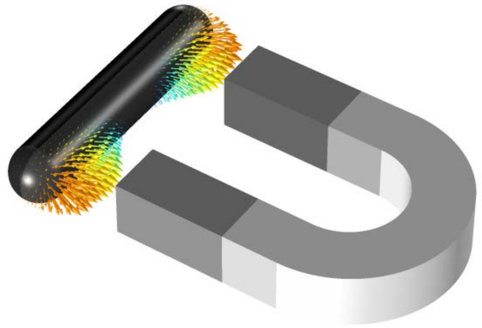
Magnets →	Magnetic Fields, No Currents
Inductors and Coils (with currents) →	Magnetic Fields
Superconductors →	Magnetic Field Formulation
Motors and Actuators →	Rotating Machinery, Magnetic



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Skin Depth, Wavelength, Relaxation Time

- Skin depth δ
- Wavelength λ
- Charge relaxation time τ

$$\delta = \frac{1}{Re\left(\sqrt{i\omega\mu_0\mu_r(\sigma + i\omega\varepsilon_0\varepsilon_r)}\right)} \approx \sqrt{\frac{2}{\omega\mu\sigma}} \approx \frac{503}{\sqrt{\sigma\mu_r f}}, \qquad \boldsymbol{J}(d) = \boldsymbol{J}_s e^{-d/\delta}$$

$$\lambda_0 = \frac{c}{f}, \qquad \lambda = \frac{\lambda_0}{n}$$

$$\tau = \frac{\varepsilon}{\sigma}, \qquad \rho_f(t) = \rho_0 e^{-t/\tau}$$

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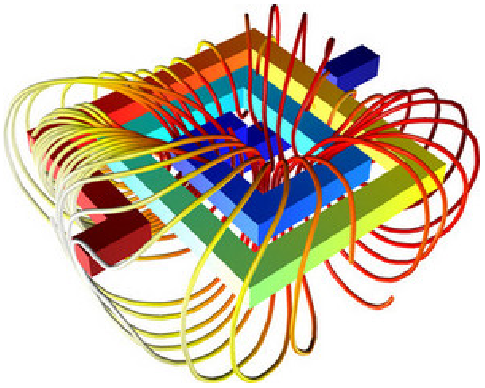
Magnets → Magnetic Fields, No Currents

Inductors and Coils (with currents) → Magnetic Fields or Magnetic and Electric Fields

Superconductors → Magnetic Field Formulation

Motors and Actuators → Rotating Machinery, Magnetic



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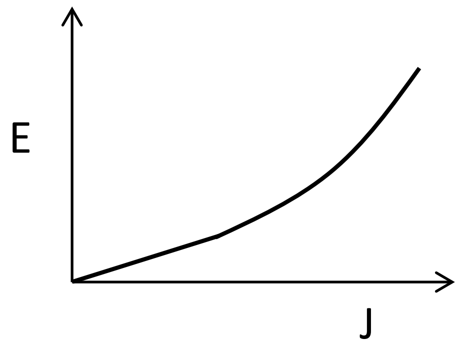

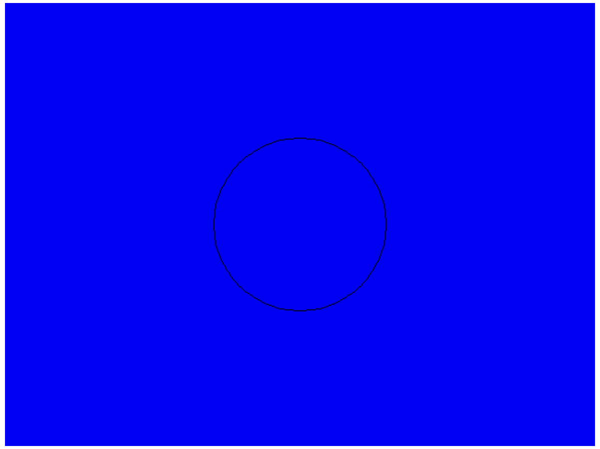

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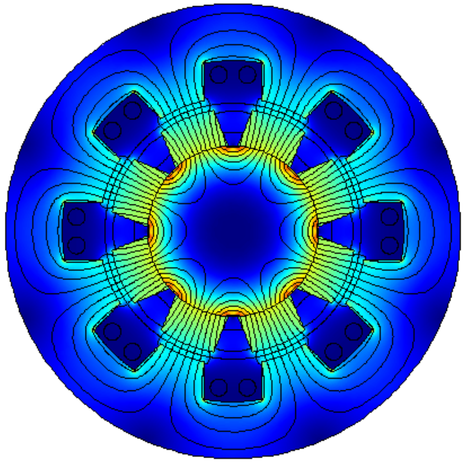

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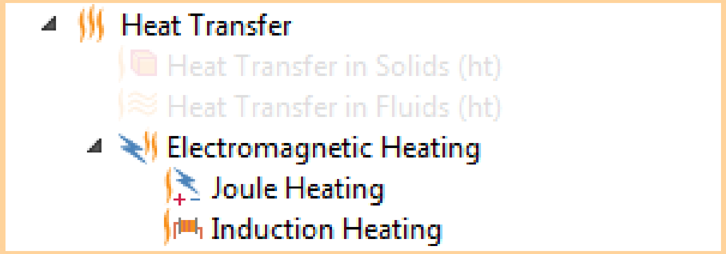
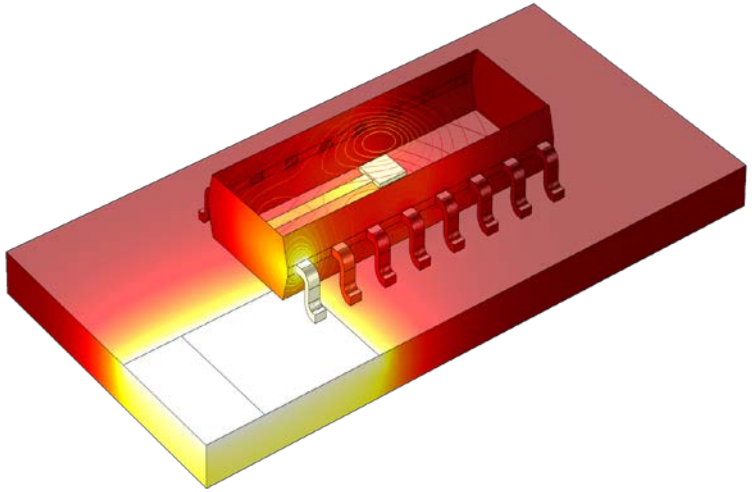
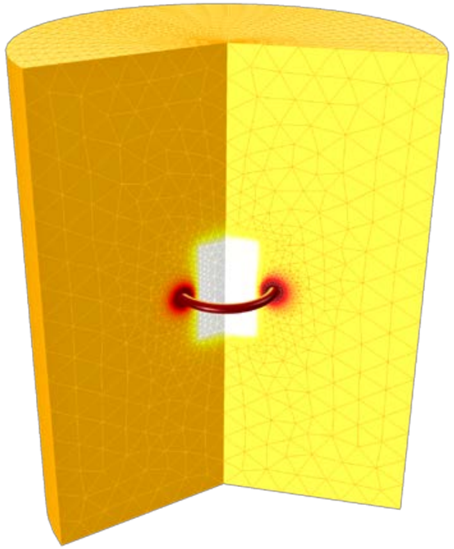
Whenever there are Electromagnetic Losses, there is a Rise in Temperature

- Specialized user interfaces and solvers address the two-way coupled frequency-domain electromagnetic and stationary or time-domain thermal problems





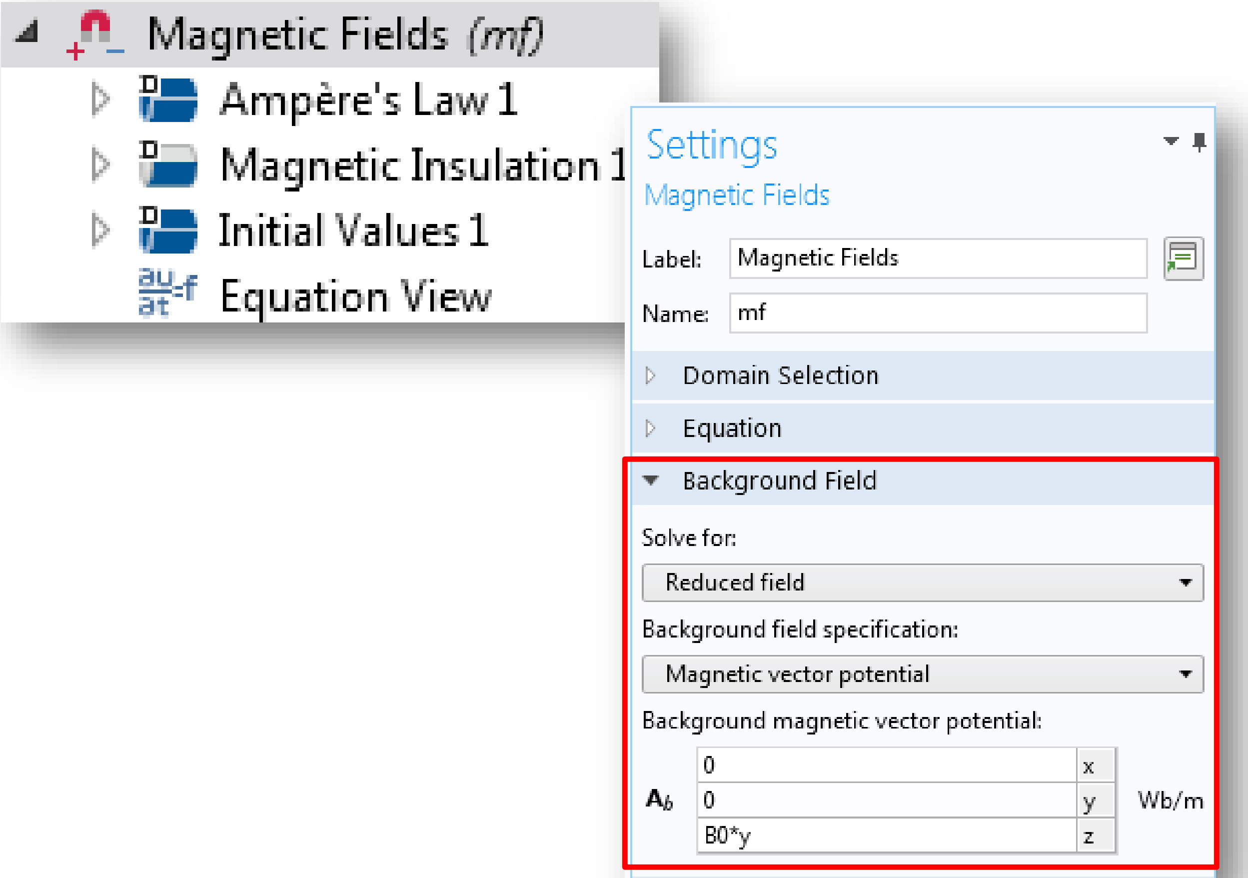
Joule Heating

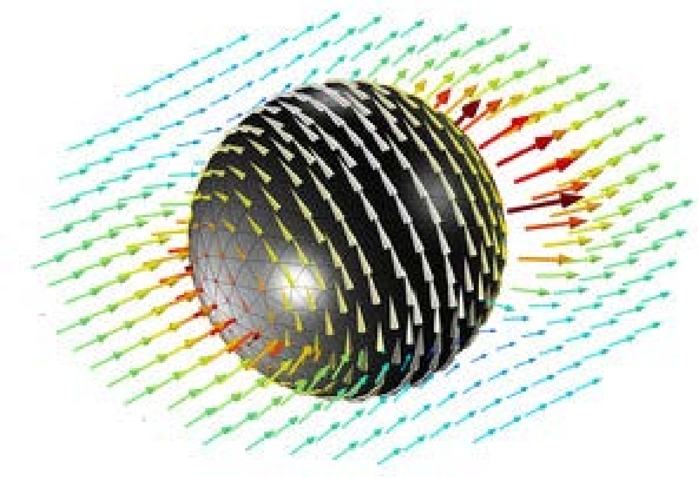


Induction Heating

Feature Overview: Domain Conditions

- Full and Reduced Field excitations





https://www.comsol.com/model/iron-sphere-in-a-13-56-mhz-magnetic-field-12835

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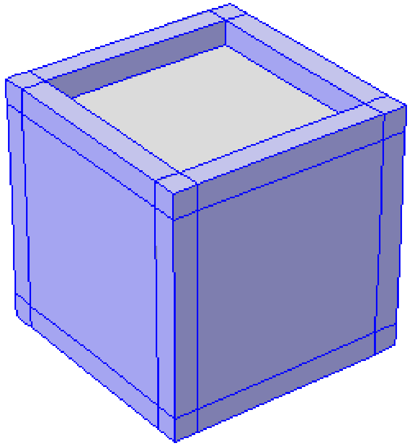
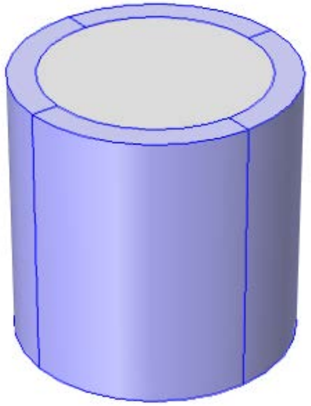
Feature Overview: Domain Conditions

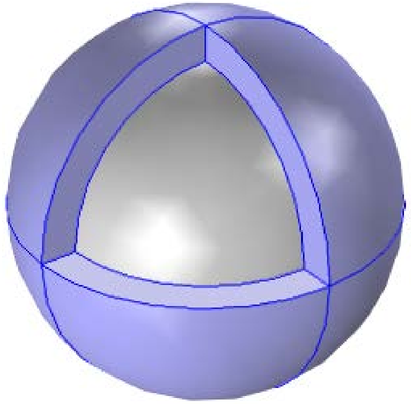
- Full and Reduced Field excitations
- Infinite Elements



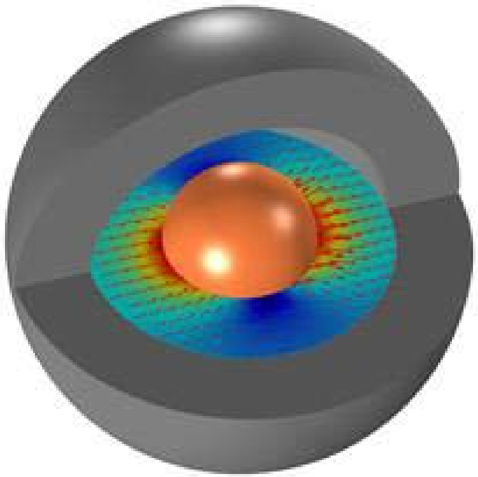
Cartesian Type



Cylindrical Type



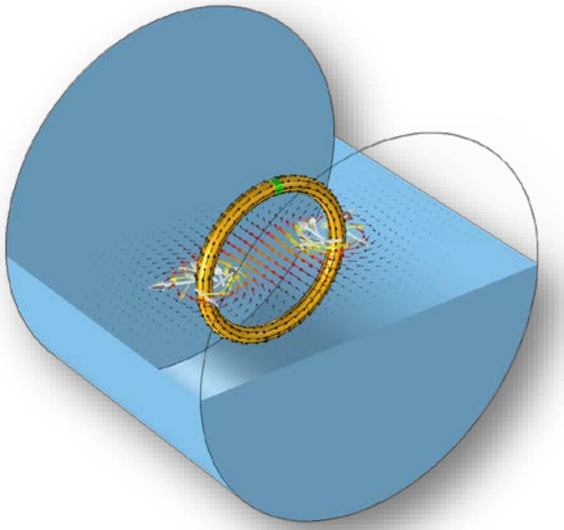
Spherical Type

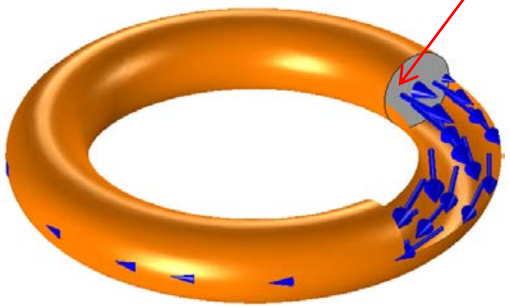


Tip: if the energy is stored in the center core, the air domain can be roughly 3 to 5 times the size of the core without Infinite Element Domain.

Feature Overview: Domain Conditions

- Full and Reduced Field excitations
- Infinite Elements
- Coils: Single Conductor Coil



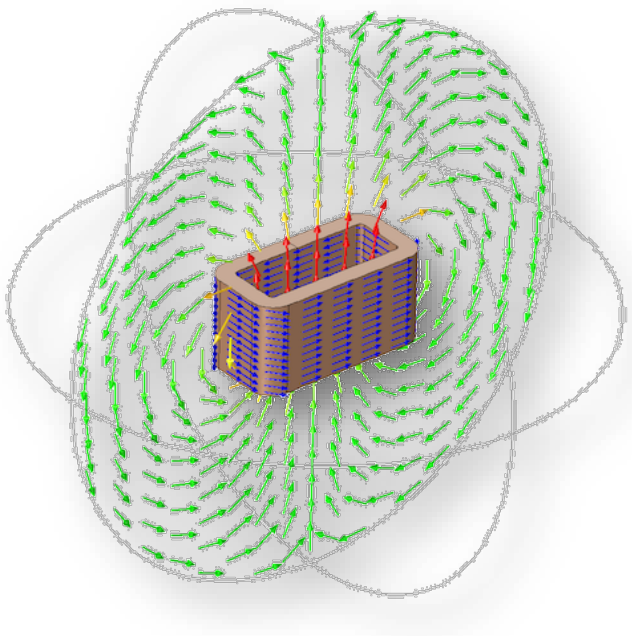


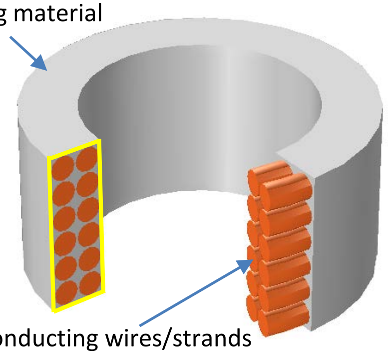
Input

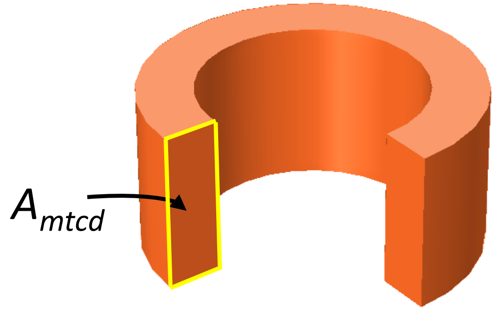
1. Specify the voltage across the boundary
2. Specify the current through the boundary
3. Options to connect to the lumped electrical circuit

Feature Overview: Domain Conditions

- Full and Reduced Field excitations
- Infinite Elements
- Coils: Homogenized Multi-Turn Coil







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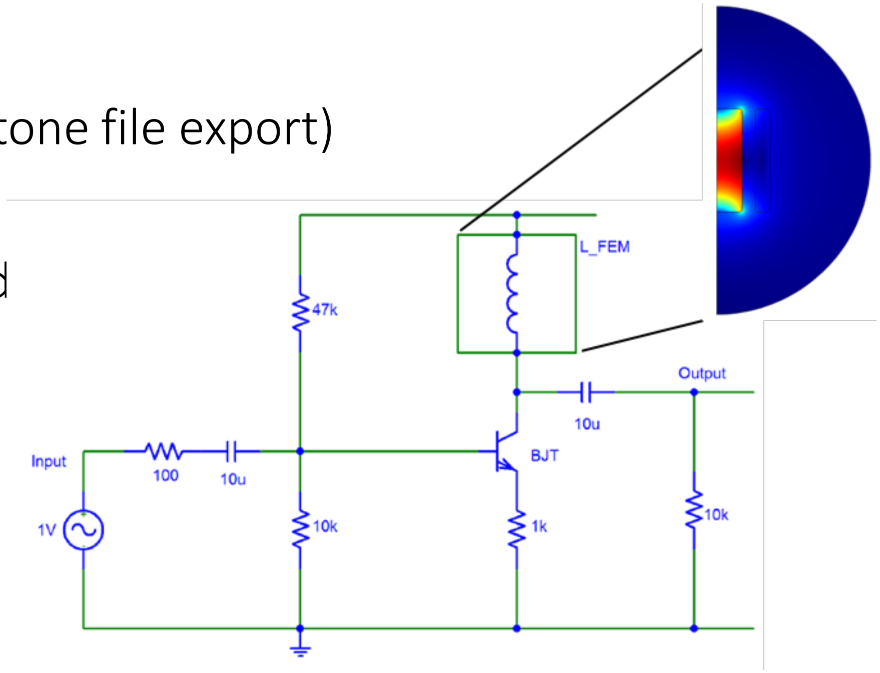
Feature Overview: Data Extraction and Imports

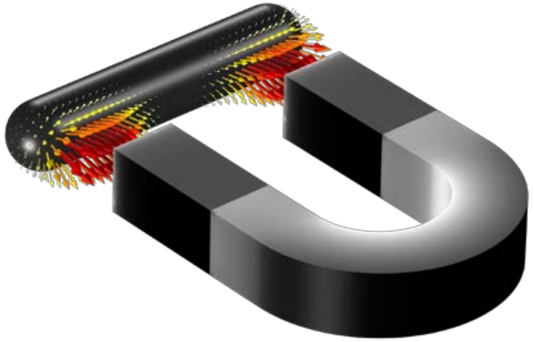
- Resistance, Capacitance, Inductance, and Mutual Inductance
- Impedance, Admittance, and S-parameters (optional Touchstone file export)
- Electromagnetic torque and force calculation due to EM field
- Coupling to Electrical Circuits (supports SPICE netlist)



Electrical Circuits

$$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$$

Lumped Parameters



Magnetic Forces

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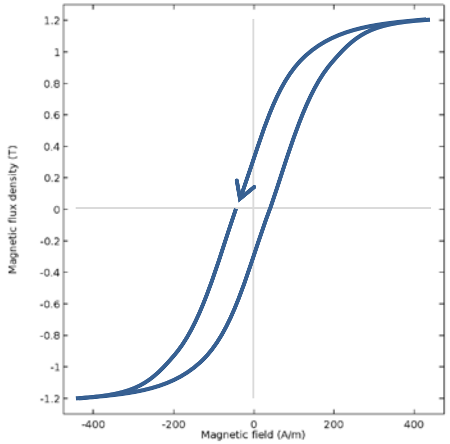
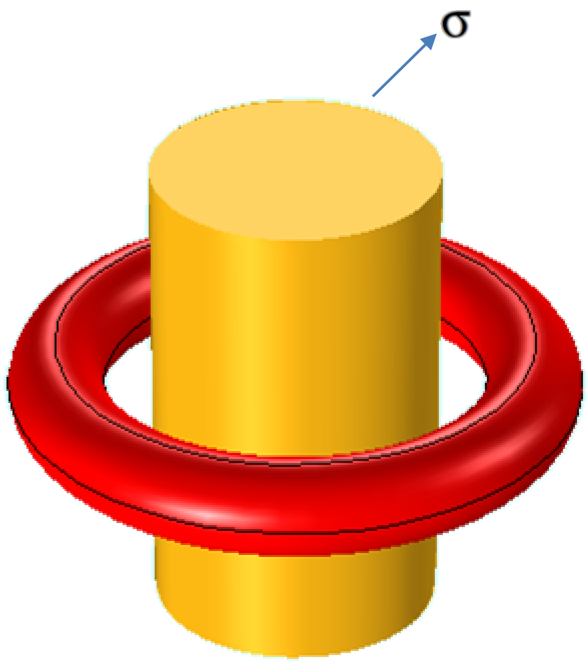
Feature Overview: Material Models

- Constitutive relations $\boldsymbol{H} \leftrightarrow \boldsymbol{B}$
  - Relative permeability (user defined)
  - Relative permeability (effective medium)
  - Magnetic losses
  - $\boldsymbol{H}(\boldsymbol{B})$ curve, $\boldsymbol{B}(\boldsymbol{H})$ curve (user defined)
  - $\boldsymbol{H}(\boldsymbol{B})$ curve, $\boldsymbol{B}(\boldsymbol{H})$ curve (external)
  - Remanent flux density
  - Magnetization
  - Effective $\boldsymbol{H}(\boldsymbol{B})$ curve
  - $\boldsymbol{H}(\boldsymbol{B})$ nonlinear permanent magnet
  - Hysteresis (Jiles-Atherton model)



- Constitutive relations $\boldsymbol{J} \leftrightarrow \boldsymbol{E}$
  - Electrical conductivity (user defined)
  - Electrical conductivity (effective medium)
  - Electrical conductivity (Archie's law)
  - (Linearized) resistivity
  - $\boldsymbol{E}(\boldsymbol{J})$ characteristic
- Constitutive relations $\boldsymbol{D} \leftrightarrow \boldsymbol{E}$
  - Relative permittivity (user defined)
  - Relative permittivity (effective medium)
  - Dielectric losses
  - Loss tangent, loss angle
  - Loss tangent, dissipation factor
  - Remanent electric displacement
  - Polarization

Demo: Inductive Heating



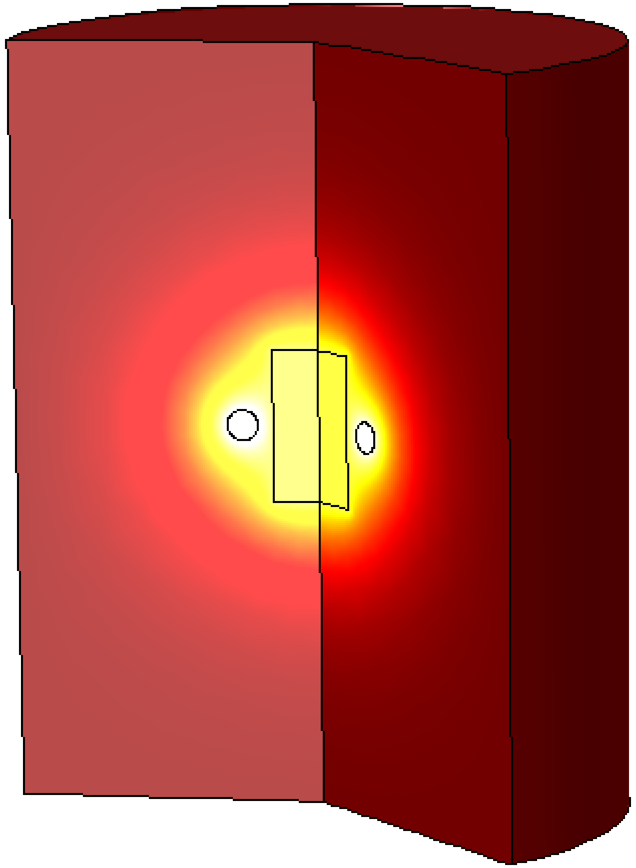
- AC current through a coil heats up the copper core:

$$\sigma = \frac{1}{[\rho_0(1 + \alpha(T - T_0))]}$$

- Multiphysics model
  - Electromagnetics: small time scale
  - Heat transfer: large time scale
- Frequency-Transient analysis

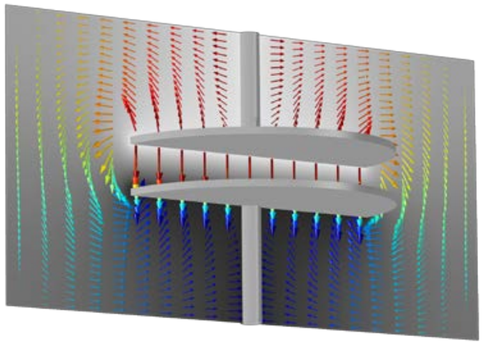
Summary of Workflow

- Select Dimension, Physics, Study
- Create/Import Geometry
- Apply Materials
- Set up Physics
- Mesh
- Solve
- Extract Results

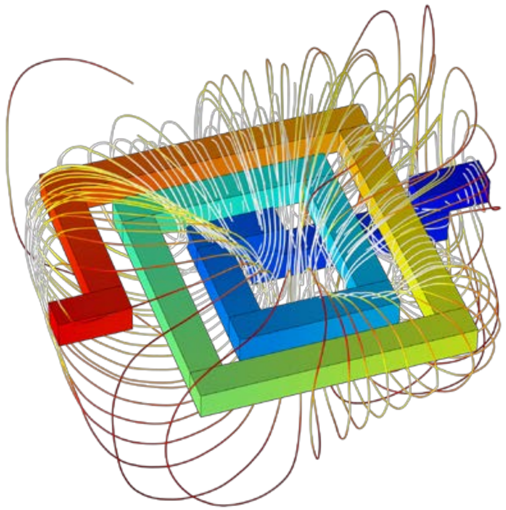


Concluding Remarks: Static Field Modeling

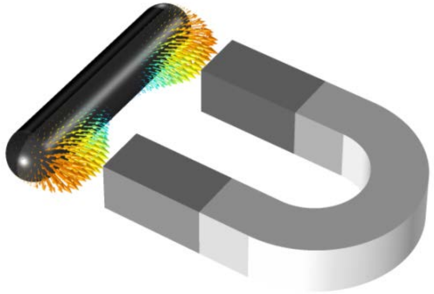
- **Electrostatics** solves for electric fields in perfect insulators
- Stationary **Electric Currents** solves for steady current flow in conductors
- Stationary **Magnetic Fields** solves for the magnetic fields around magnets, and the fields around current carrying objects



Parallel Plate Capacitor, Electrostatics



Inductor, DC current flow and Magnetostatics



Permanent Magnet, Magnetostatics

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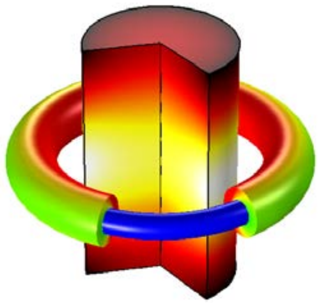
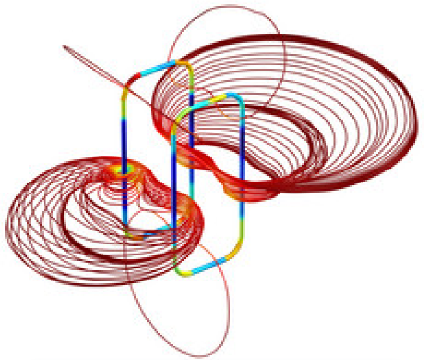
Concluding Remarks: Low Frequency Modeling

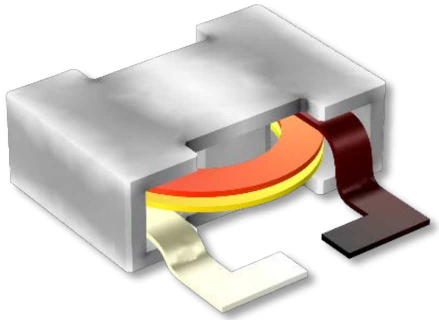
- **Electric Currents** solved in the frequency domain considers both conduction and displacement currents in conductive and dielectric media
- **Magnetic Fields** can be solved for in the frequency domain to find the conduction, displacement, and induction currents
- **Magnetic and Electric Fields** can be solved to find magnetic and electric fields resulting from an applied electric potential



Inductive Heating, Magnetic Fields



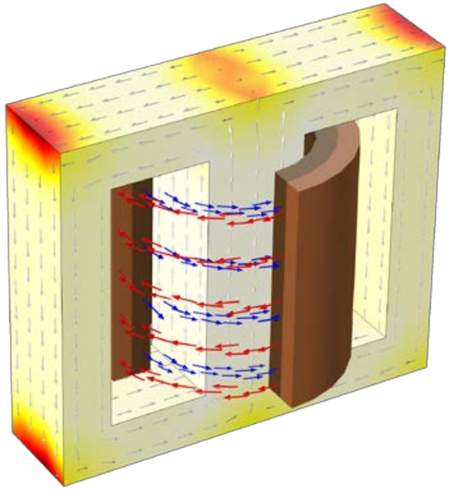
Mutual Inductance, Magnetic Fields Analysis



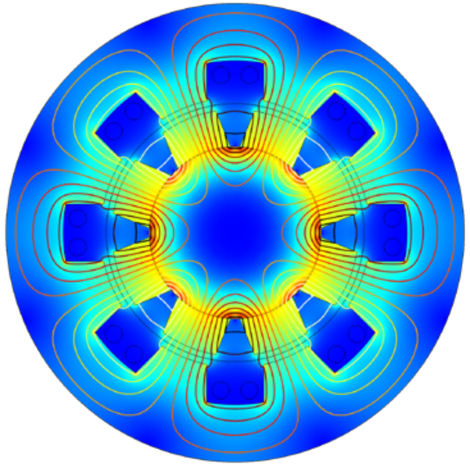
Inductor, Magnetic and Electric Fields

Concluding Remarks: Transient Modeling

- Transient **Electric Currents** solves for conduction and displacement currents in conductive and dielectric media
- Transient **Magnetic Fields** is suitable for modeling current pulses and nonlinear material response to field strength
- **Rotating Machinery** considers the rotary velocity and acceleration of material



E-Core Transformer, Transient Magnetic Fields



Generator, Rotating Machinery

Questions?