Introduction to Electromagnetic Field Simulation

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University *of Ljubljana*
Faculty *of Mechanical Engineering*

CAPACITIES

e-infrastructure

Technical Applications of Electromagnetics

Electromagnetism is never done for its own sake, it is used to manipulate/observe something in some other physical domain.

Electromagnetic energy can easily be transported and converted into other energy forms.

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Technical Applications of Electromagnetics
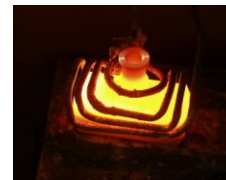
Transfer
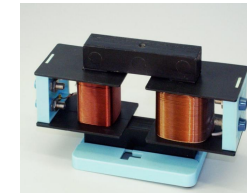
Transformation

Energy

Information

EMI/EMC

Image Source: Wikipedia

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Technical Applications of Electromagnetics

Transfer   Transformation

Energy

•Transformer
•Inductive Charging
•Power connectors

•Actuators
•Inductive Heating
•Microwave Heating

EMI/EMC

Information

•(Power) Electronics
•Antenna Systems
•Signal Lines
•Connectors

•Radar
•Sensors
•NMR

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What is electromagnetism: Maxwells Equations

- The equations of motion for electromagnetics are Maxwells equations:

$$\vec{\nabla} \cdot \vec{D} = \rho, \quad \vec{\nabla} \times \vec{E} + \partial_t \vec{B} = 0,$$
$$\vec{\nabla} \cdot \vec{B} = 0, \quad \vec{\nabla} \times \vec{H} - \partial_t \vec{D} = \vec{j}.$$

- These need to be supplemented by constitutive equations, i.e. material laws like:

$$\vec{D} = \epsilon \, \vec{E},$$
$$\vec{H} = \frac{1}{\mu} \vec{B},$$
$$\vec{j} = \sigma \, \vec{E}, \cdots$$
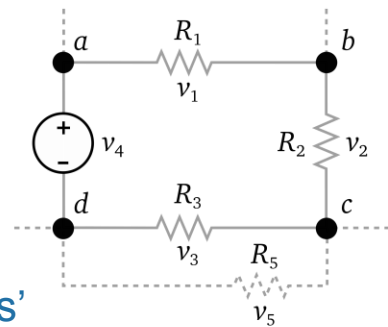
- This is a quite complicated system of equations!

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What is electromagnetism

- Understand implications/solutions of Maxwells equations → understand the applications of electromagnetism
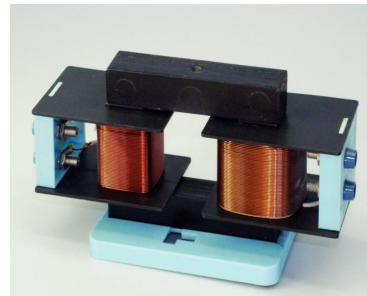
  - Kirchhoffs laws for electrical networks

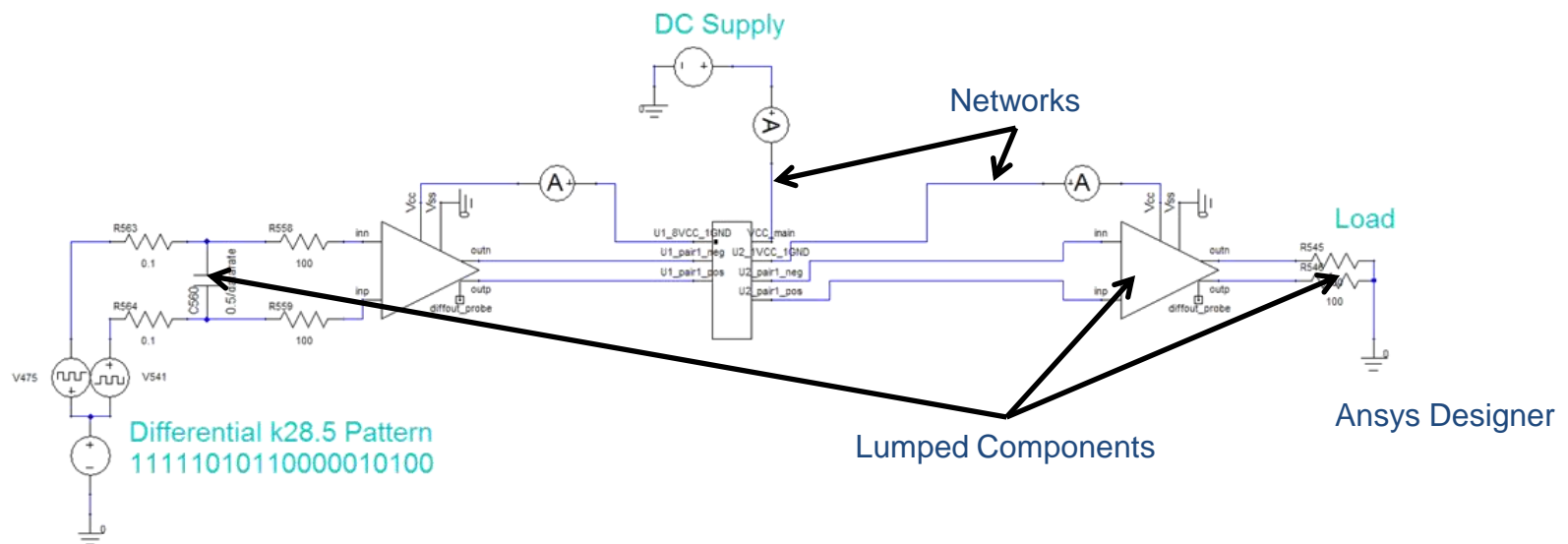 - Electromagnetic waves at 'high frequencies'

  - Induction

  - Electric and magnetic forces

Image Source: Wikipedia

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Ways to simulate electromagnetism: Circuit Simulation

- In electronic and electrical engineering one is used to schematic circuits and circuit simulation (system simulation).

- Fast simulation.
- Need input quantities like analytical expressions (LRC…), matrices, behavioral models (e.g. IBIS) etc.

- → 0-dimensional Systems, solve ODEs (ordinary differential equations)

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Ways to simulate electromagnetism:
The ANSYS Portfolio

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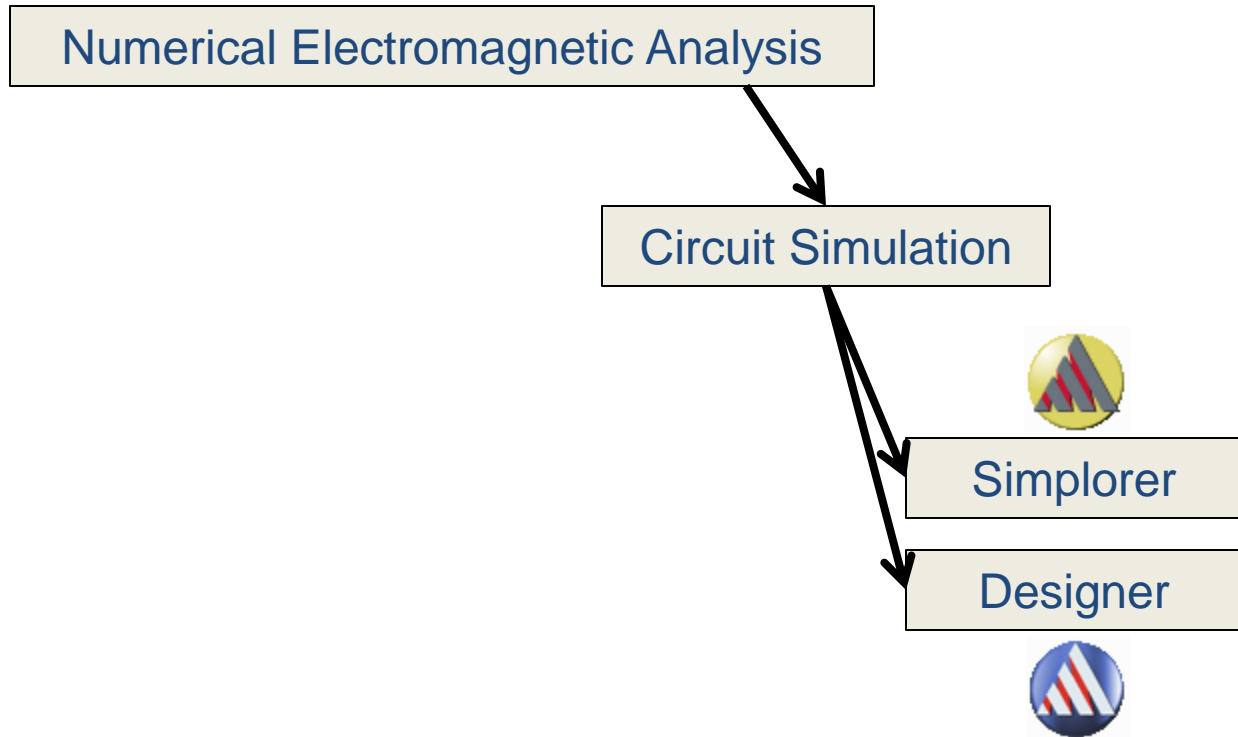
Simplorer

- Power Electronics circuit simulator
  - Libraries of PE components
- Different Physical Domains
  - Electrical
  - Magnetic
  - Mechanical
  - Thermal
  - Hydraulic
- Different ways of modeling
  - State Space Models
  - Block Diagrams
  - State Graphs
  - Digital/VHDL
  - C
  - Matlab

- Reduced Order Models from
  - Ansys Electromagnetics Products
  - Ansys Mecanical
  - Ansys CFD
  - Ansys Icepak

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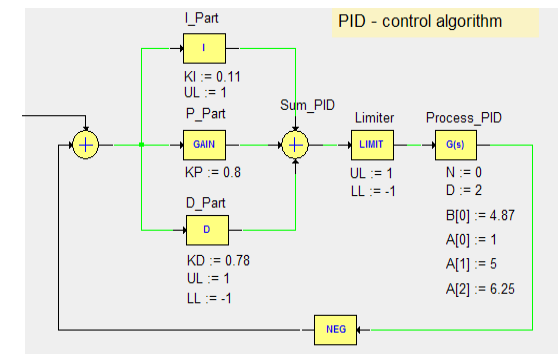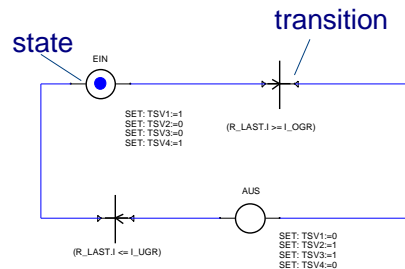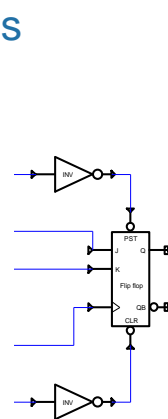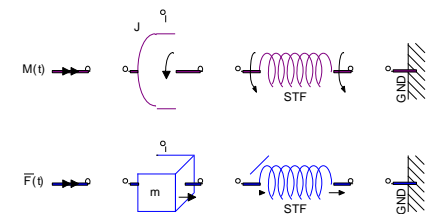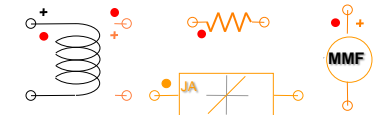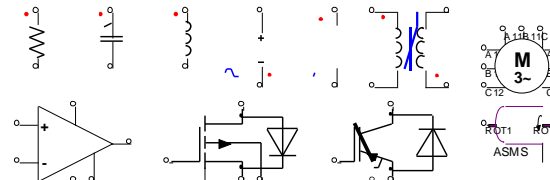
Designer

- Integrates ANSYS HF tools into a seamless HF system simulation
  - Solves
    - Time / frequency circuits and systems

- Uses
  - State Space or convolution time domain spice solver
  - Harmonic Balance frequency domain solver
  - 2D / 3D Method of Moment solver
- Applications
  - Time and / or frequency domain circuit analysis
  - Signal Integrity
  - Antenna Arrays
  - RF IC simulation

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Ways to simulate electromagnetism: Field Simulation

- Electromagnetic fields are distributed quantities → in many situations the actual geometric dimensions influence the behavior of the system:
  - The behavior of an electric engine depends on its geometry and the materials it is made of.
  - Antennas depend on the geometry.

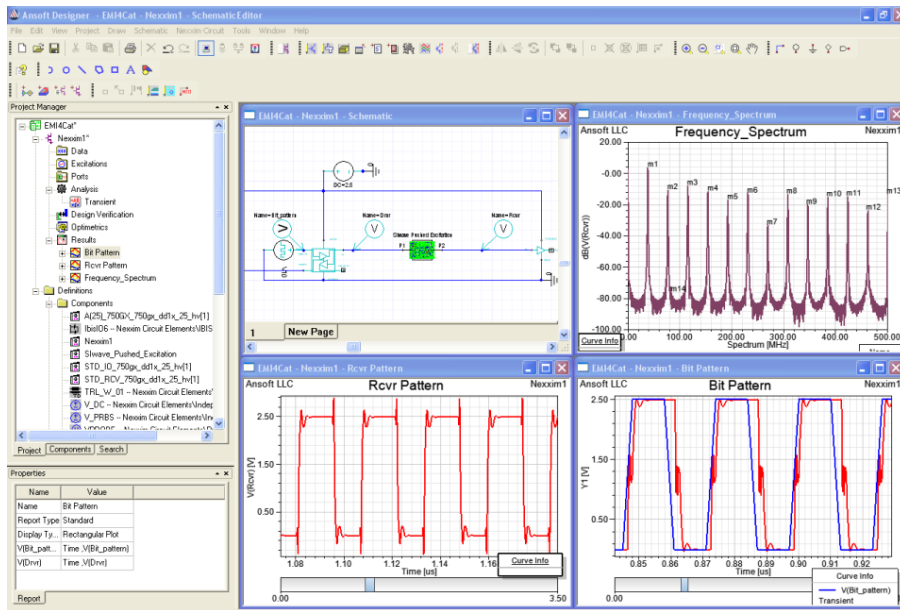- → 2D/3D field simulation, solve PDEs (partial differential equations)

Ansys HFSS

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Ways to simulate electromagnetism:
The ANSYS Portfolio

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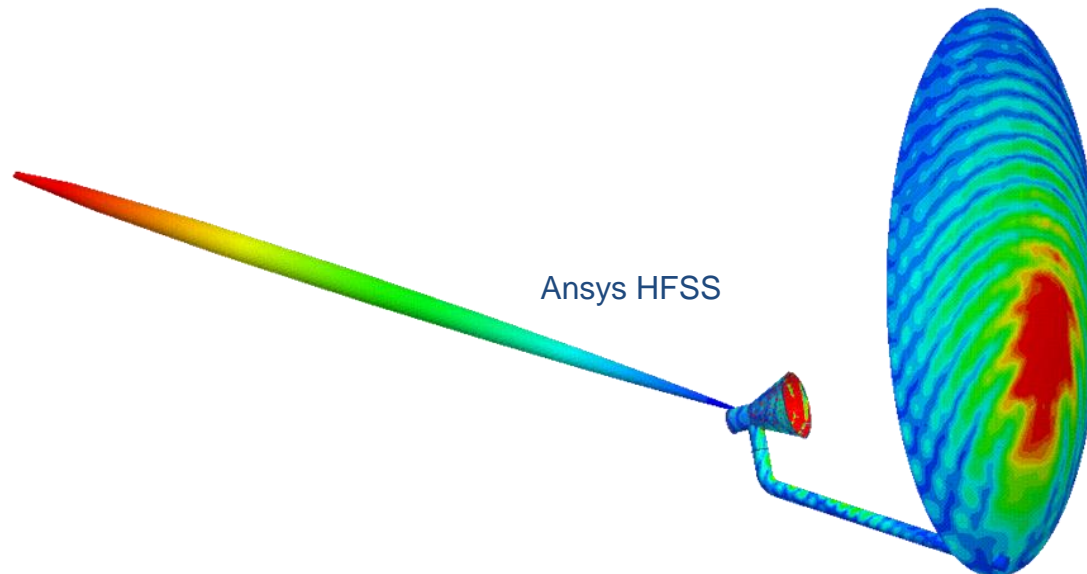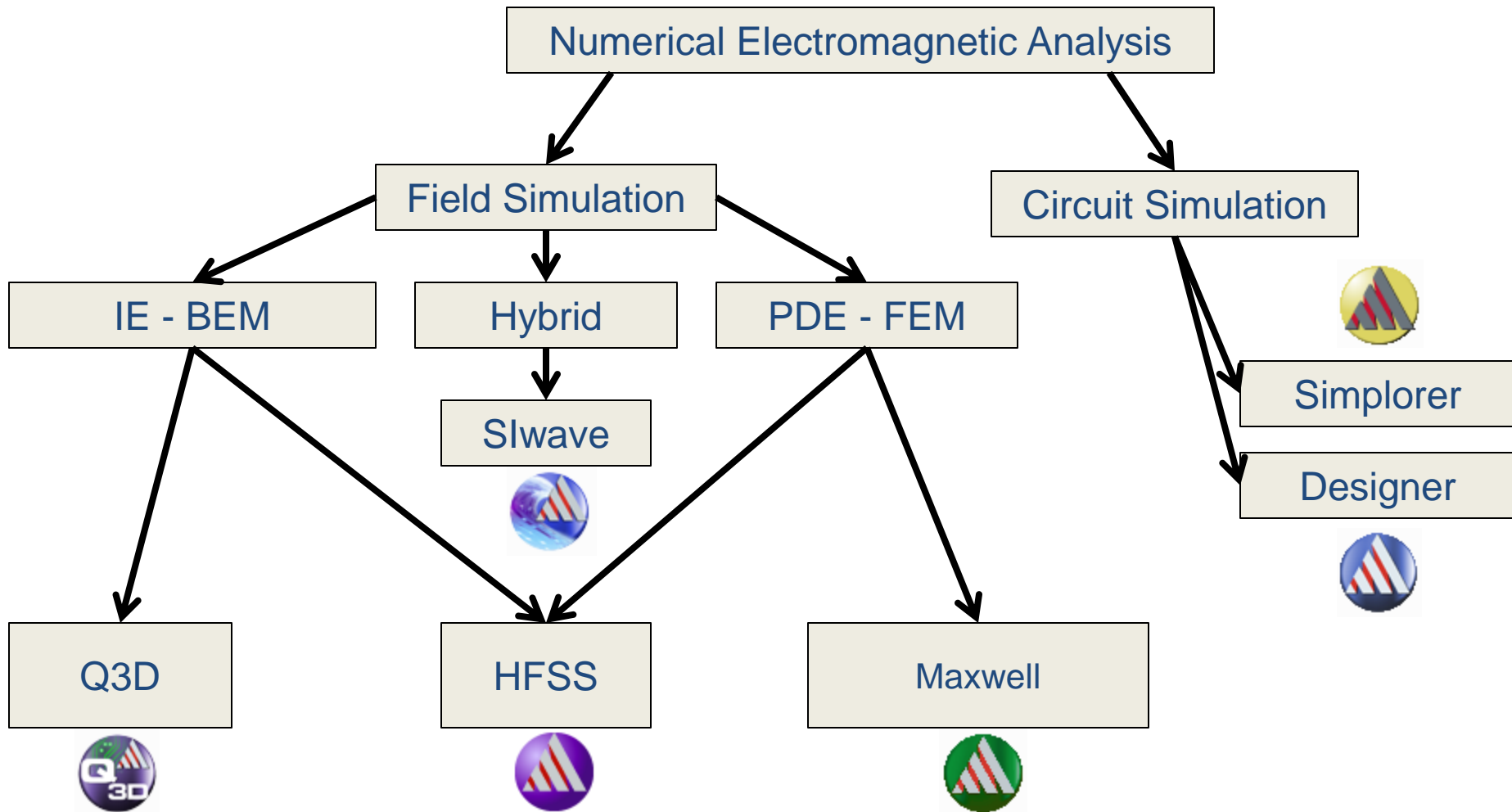
HFSS – High Frequency Structure Simulator

- 3D Field Solver
  - 3D Finite Element Method (FEM)
  - Boundary Integral (IE)
  - Mesh Process: Adaptive
- Advanced Boundary Types
  - Radiation and Perfectly Matched Layers
  - Symmetry, Finite Conductivity, Infinite Planes, RLC, and Layered Impedance
- Advanced Material Types
  - Frequency dependent
  - Anisotropic
- Post Processing and Report Type
  - SYZ parameters
  - Field display
  - Near Field/Far Field

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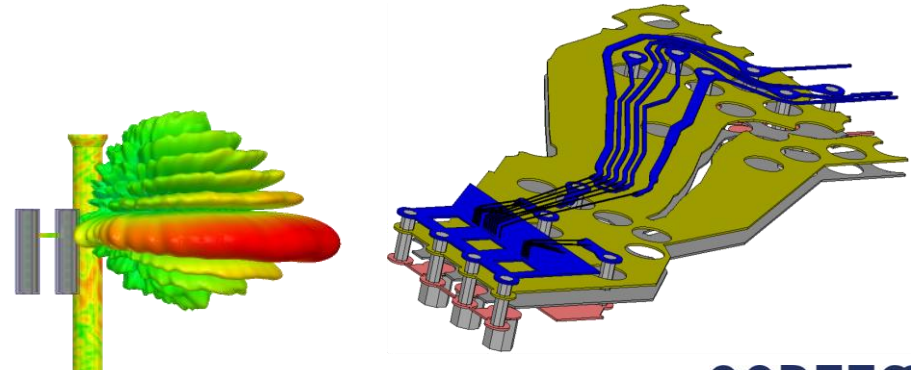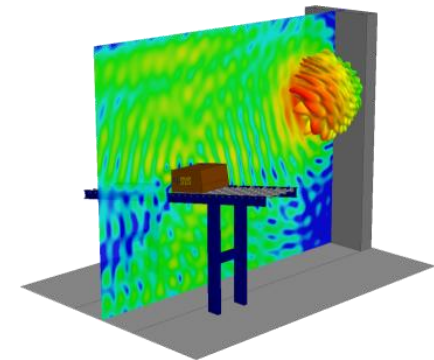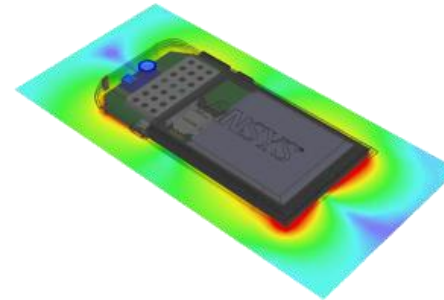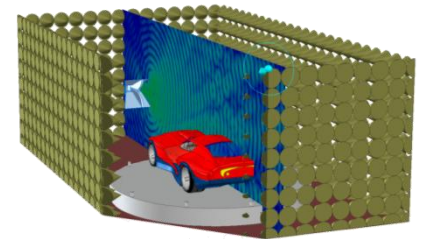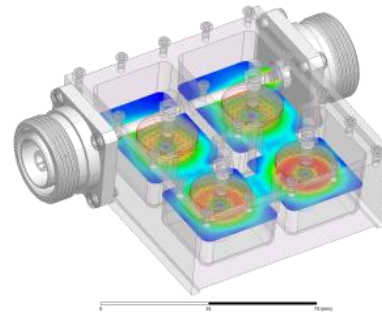
Maxwell

- 3D Field Solver
  - 3D/2D Finite Element Method (FEM)
  - Large Motion
  - Mesh Process: Adaptive
- Advanced Boundary/Excitations
  - Symmetry, Master-Slave
  - Impedance Boundary Condition
  - External Circuits/Cosimulation
- Advanced Material Types
  - Non-linear, Anisotropic
  - 3D Vector Hysteresis Model
- Post Processing and Report Type
  - Currents, Voltages, Forces Torques
  - Field display
  - Losses

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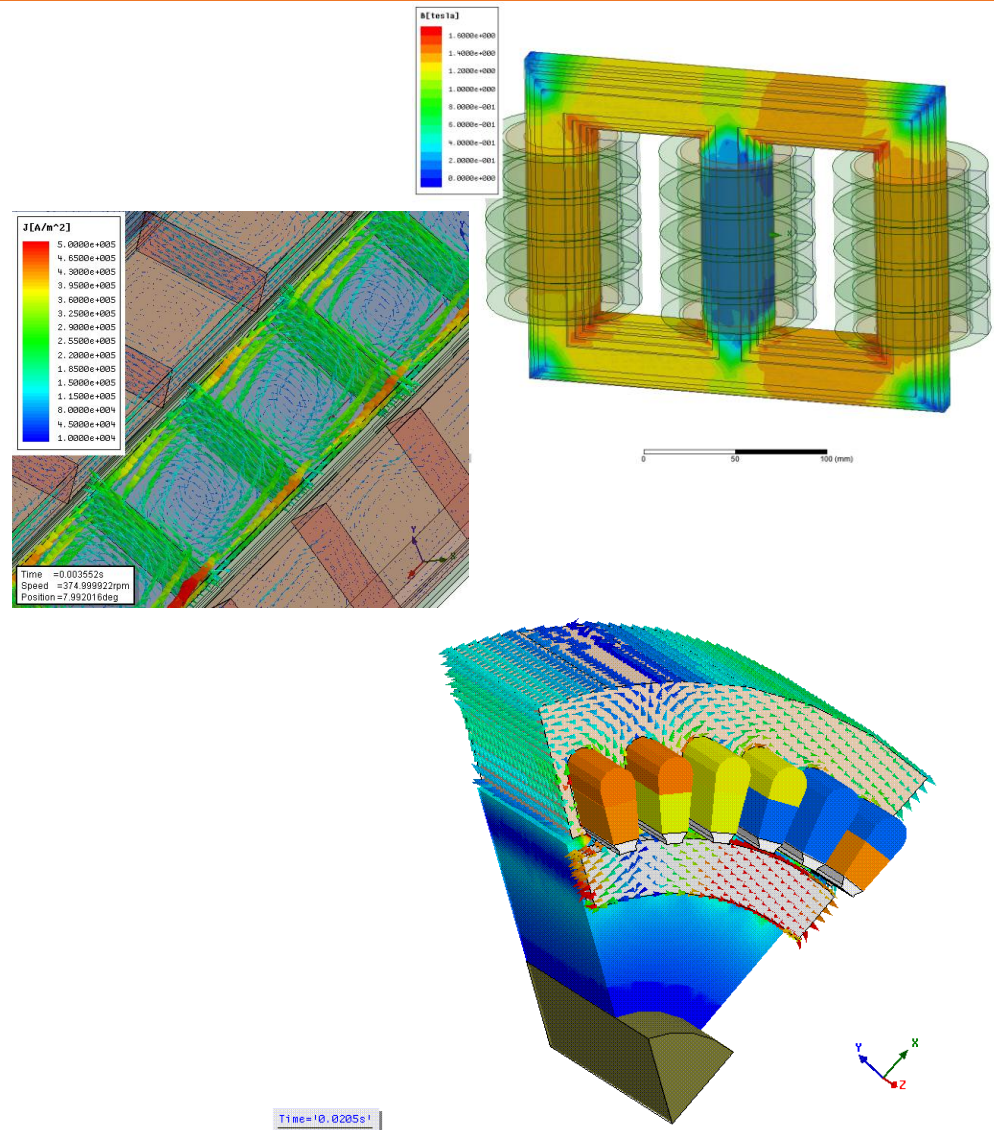
Q3D Extractor

- Quasi-static electromagnetic-field solver
  - DC → (Electrical Wavelength)/8
  - RLGC Parameter extraction
- Creation of equivalent circuit models
  - HSpice®, PSpice®, Spectre®
  - Cadence DML, Intel LCF & IBIS .pkg model
  - Simplorer® SML models
- Co-simulation with Ansoft Designer
- Includes 2D Extractor™ quasi-static 2D field solver

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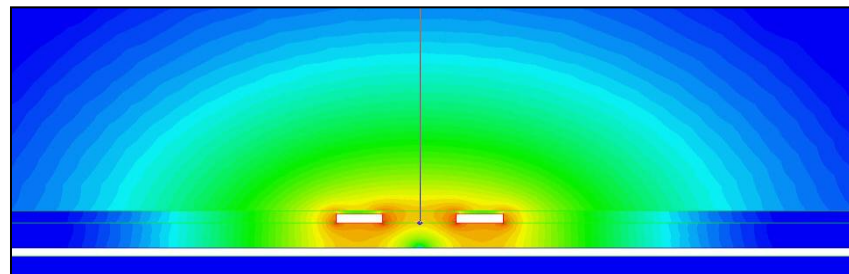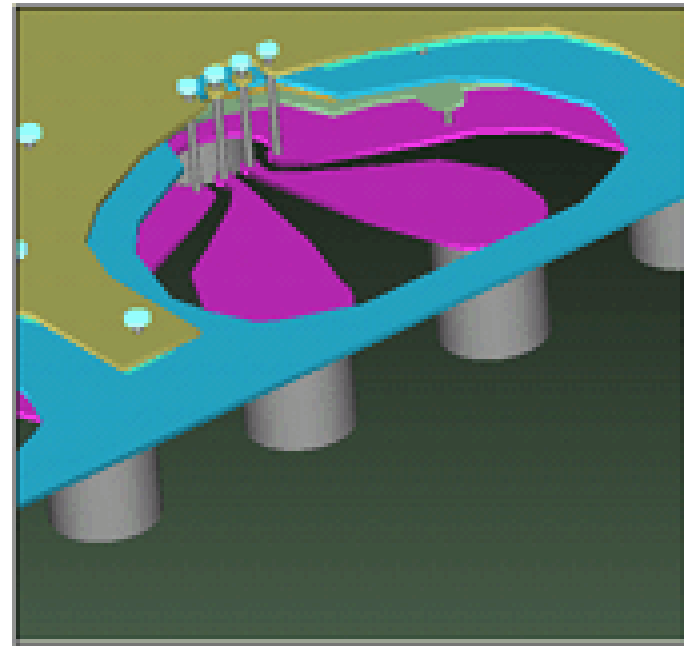
Siwave

- Pre or Post-layout analysis tool
- Solves
  - Entire multi-layer Printed Circuit Board (PCB)
  - Entire leaded Integrated Circuit (IC) Package
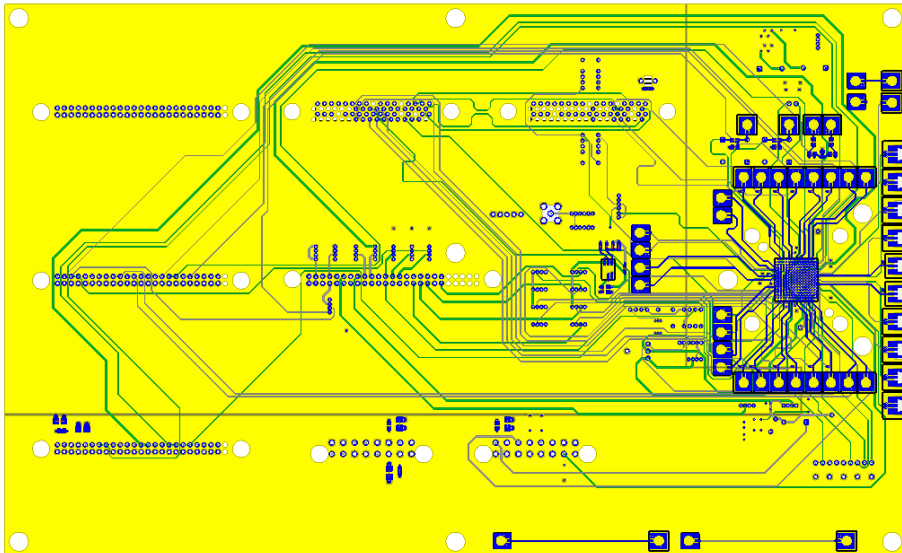
- Uses
  - 2D FEM for Power/Ground plane structures
  - Specialized 2D solver for Traces
  - 3D quasi-static solutions for transition (vias, solderballs, etc.)

- Applications
  - PCB signal integrity calculation
  - PCB power delivery characterization
  - Evaluation of de-coupling capacitor location
  - Circuit model generation
  - DC current and voltage distribution on PCB

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Ways to simulate electromagnetism: System Simulation

- Combination of circuit and field simulation:
  - Simulation of a PCB with transistors and other electronic components
  - Simulation of electrical behavior of a whole car
- → System Simulation = Circuit Simulation + Field Simulation
  - Reduced order models
  - Cosimulation
- Efficient way to model large Systems with the desired accuracy
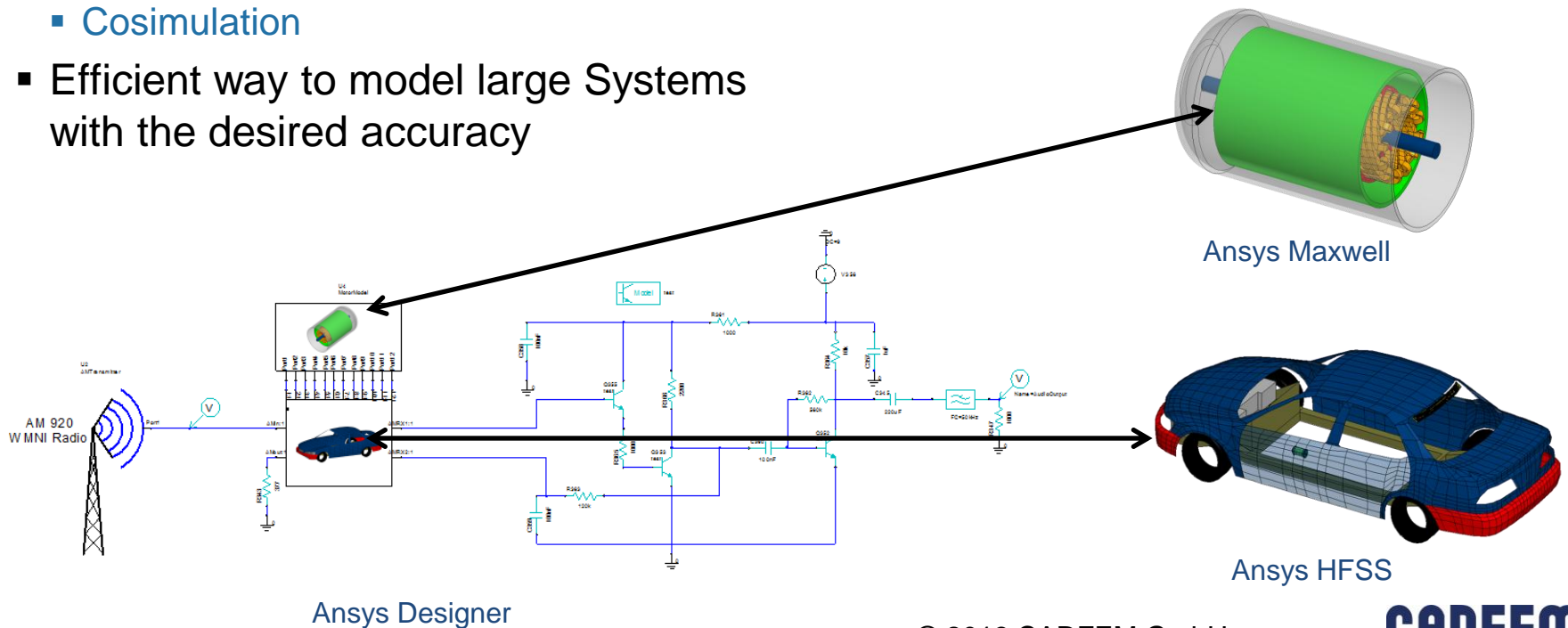
Ansys Maxwell

Ansys HFSS

Ansys Designer

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What is electromagnetism: Maxwells Equations

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$$\vec{\nabla} \cdot \vec{D} = \rho, \quad \vec{\nabla} \times \vec{E} + \partial_t \vec{B} = 0,$$
$$\vec{\nabla} \cdot \vec{B} = 0, \quad \vec{\nabla} \times \vec{H} - \partial_t \vec{D} = \vec{j}.$$

- These need to be supplemented by constitutive equations, i.e. material laws like:

$$\vec{D} = \epsilon \, \vec{E},$$
$$\vec{H} = \frac{1}{\mu} \, \vec{B},$$
$$\vec{j} = \sigma \, \vec{E}, \cdots$$

- This is a quite complicated system of equations!

Source: Wikipedia

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What is HF?

- High Frequency electromagnetics is concerned with the propagation of electromagnetic waves.

$$\vec{\nabla}\times(\tfrac{1}{\mu}\vec{\nabla}\times\vec{E})-\omega^2\varepsilon\vec{E}=0$$

- Electromagnetic waves propagate with a finite velocity, the speed of light c.
- To a frequency f one can associate a wave length λ=c/f

frequency	DC	1 Hz	1 kHz	1 MHz	1 GHz	???
wave length	--	3e8 m	300 km	300 m	0.3 m	???

- If the characteristic size d of a part under consideration is comparable to the wave length (about d > λ/10) wave effects become important.

problem scale

0   λ/10

| quasi static | intermediate | full wave |

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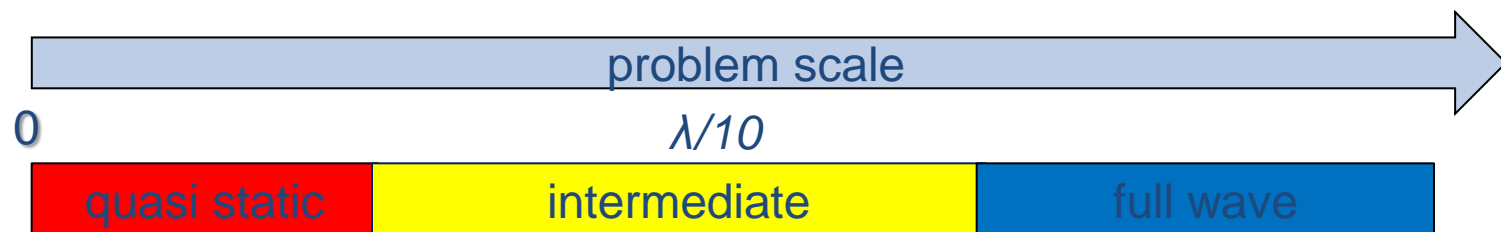
HF Equation

- For linear, but maybe frequency dependent, material properties the time can be separated out of Maxwell's equations. This corresponds to replacing time derivatives

$$\partial_t \longrightarrow i\omega$$

- Maxwell's equations can then for ω≠0 be reduced to the single equation

$$\vec{\nabla} \times \left(\frac{1}{\mu} \vec{\nabla} \times \vec{E} \right) - \omega^2 \epsilon \vec{E} = -i\omega \vec{j}$$

- The double curl operator on the left hand side is negative semi definite. For this reason the equation has unique solutions for ω≠0.
- This equation is solved in HFSS.

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What can be gained by doing LF?

- At low frequencies one can neglect certain time derivatives, which simplifies the equations. This allows to consider non-linear material laws and motion.

$$\vec{\nabla} \cdot \vec{D} = \rho, \quad \vec{\nabla} \times \vec{E} + \partial_t \vec{B} = 0,$$
$$\vec{\nabla} \cdot \vec{B} = 0, \quad \vec{\nabla} \times \vec{H} - \cancel{\partial_t \vec{D}} = \vec{j}.$$

Image Source: Wikipedia

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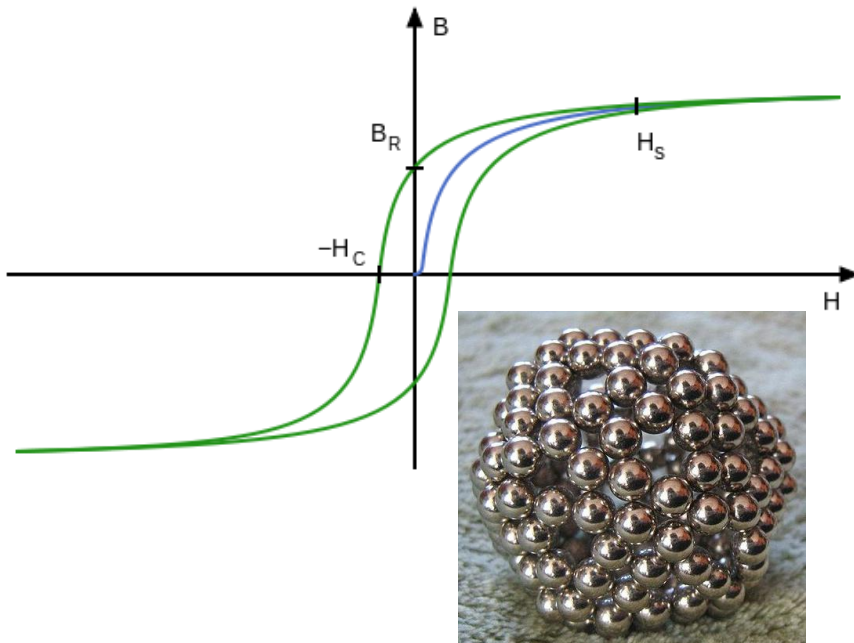
LF Equations in (A,Φ) formulation

- There are two potential formulations, the (A,Φ) and the (T,Ω) formulation.
- The (A,Φ) formulation starts from

$$\vec{\nabla} \cdot \vec{B} = 0$$

- This together with Faraday's law implies that E and B can be derived from a vector potential A and a scalar potential Φ

$$\vec{B} = \vec{\nabla} \times \vec{A}$$
$$\vec{E} = -\vec{\nabla}\Phi - \partial_t \vec{A}$$

- This is the most general solution of the two homogenous equations in Maxwell's equations.

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LF equations in (A,Φ) formulation

- Ampere's law then turns into

$$\vec{\nabla} \times \left(\frac{1}{\mu} \vec{\nabla} \times \vec{A} \right) = \vec{j}$$

- This is again very similar to the HF equation, but with zero frequency. Note that the permeability can depend non linearly on the magnetic field and furthermore that this equation is still in the time domain!

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LF equations in (A,Φ) formulation

- However, for given potentials (A,Φ) and an arbitrary scalar field Λ the there is a gauge transformation

$$\vec{A}' = \vec{A} - \vec{\nabla}\Lambda$$
$$\Phi' = \Phi + \partial_t \Lambda$$

  leading to equivalent potentials. I.e. the potentials (A,Φ) and (A',Φ') lead to the same fields E and B.

- Conversely, the field equation can only be solved if the current is conserved

$$\vec{\nabla} \cdot \vec{j} = 0$$

- All of this implies that

$$\vec{\nabla} \times \frac{1}{\mu} \vec{\nabla} \times$$

  is a singular differential operator.

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LF equations in (T,Ω) formulation

- The starting point for the (T,Ω) formulation is the current conservation, which implies that there is a vector potential T such that

$$\vec{j} = \vec{\nabla} \times \vec{T}$$

- The magnetic field H can the be written in terms of the potential Ω

$$\vec{H} = \vec{T} + \vec{\nabla}\Omega$$

- The field equations are then different in conducting and non-conducting regions:

$$\vec{\nabla} \times \left(\frac{1}{\sigma} \vec{\nabla} \times \vec{T} \right) + \partial_t (\mu(\vec{T} + \vec{\nabla}\Omega)) = 0 \ \bigg| \ \vec{T} = 0$$
$$\vec{\nabla} \cdot (\mu(\vec{T} + \vec{\nabla}\Omega)) = 0 \qquad\qquad \bigg| \ \vec{\nabla} \cdot (\mu\vec{\nabla}\Omega) = 0$$

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LF equations in (T,Ω) formulation

- Again there are gauge transformations of (T,Ω) which leave the physics unchanged

$$\vec{T}' = \vec{T} + \vec{\nabla}\Lambda$$
$$\Omega' = \Omega - \Lambda$$

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Ways to simulate electromagnetism: FEM Method

- Need to discretize field equations
  - Translate differential equation to algebraic equations
  - Split one "big" task into a finite number of "simple" subtasks

- Finite element method (FEM)
  - Discretize space by tetrahedrons.
    → Easy to model complicated objects
  - Discretize differential operators like

$$\vec{\nabla} \times \left(\tfrac{1}{\sigma} \vec{\nabla} \times \vec{T} \right)$$
$$\vec{\nabla} \cdot (\mu \vec{\nabla} \Omega)$$

  that appear in the field equations

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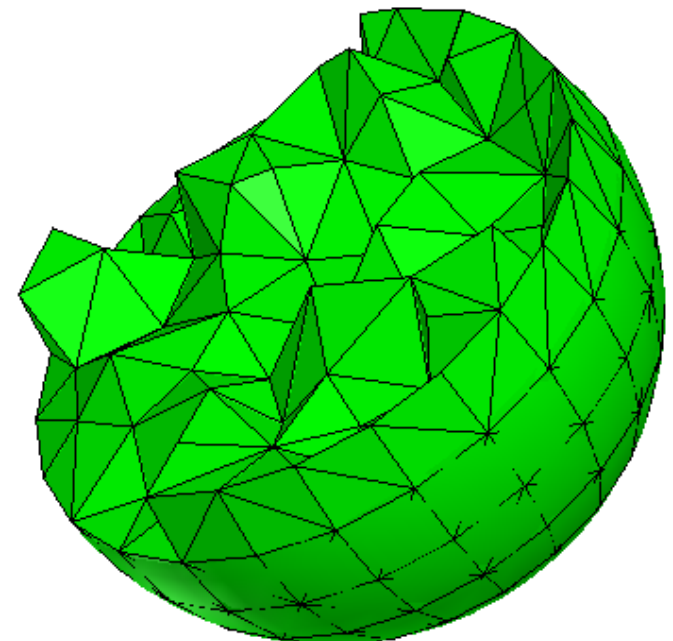
Ways to simulate electromagnetism: FEM Method

- The vector potential T encodes the current I through the triangular face of a tetrahedron with the help of Stoke's theorem

$$I = \oint \vec{T} \cdot d\vec{s}$$

- For this reason it is natural to take

$$T_{ij} = \int_{i}^{j} \vec{T} \cdot d\vec{s}$$

along the edges as degrees of freedom. Those are the edge degrees of freedom which are stored at the 6 midside nodes of a tetrahedra.

- Scalar fields are stored at the 4 vertices of the the tetrahedra.

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Ways to simulate electromagnetism: FEM Method

- The differential operators can be derived by varying the action

$$\int_V dV \; \frac{1}{\sigma} \; (\vec{\nabla} \times \vec{T})^2$$

$$\int_V dV \; \mu(\vec{\nabla}\Phi)^2$$

- This allows to discretize the differential operators in each tetrahedron using the discretized degrees of freedom.

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Boundary Conditions LF

- For a scalar field Neumann boundary conditions are free boundary conditions. From the action formulation it follows

$$\vec{n} \cdot \vec{\nabla} \Omega = 0$$

This implies that the magnetic field is parallel to the boundary if there are no boundary conditions specified.

- There are many other boundary conditions that can be specified
  - (Zero) Tangential H field
  - Insulating
  - Symmetry/Master-Slave

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Excitations LF

- In LF electromagnetics systems are typically driven by voltage and current sources.

- Currents flow in the volume and are either subject to skin- and proximity effects or flow through stranded conductors

- Furthermore objects can be in motion leading to additional inductive effects.

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Boundary Conditions HF

- The natural boundary conditions are perfect E
- There are many more boundary conditions
  - Radiation
  - Perfect E, perfect H
  - Finite Conductivity
  - Impedance/Lumped RLC
  - Symmetry/Master-Slave

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Excitations

- In HF electromagnetics systems are excited by incident waves, voltage and current sources.

- Incident waves can either enter through a radiation boundary or through a wave guide.

- Waves entering through wave guides are described by wave ports.

- Because of high frequencies the skin depth is typically very small compared to the geometric dimensions of the system under consideration. For this reason currents are typically modeled as surface currents.

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