Software Methods and Tools for the Design and Optimization of Electromechanical Devices

Lecture 1: Design Tools for Electromagnetic Devices

From Oersted to Today

Outline

- Introduction
- Industrial Needs versus Scientific Knowledge
- Models
- The First Age - Discovery
- The Second Age – Theory and Experiment
- The Third Age – Calculation post 1880
- The Fourth Age – Computational Electromagnetics from 1940

Introduction

- Electro-mechanical systems form one of the bases of modern society
- Convenient energy transportation
- Flexibility in energy usage
- Provide freedom in process operation
- But
  - To create them needs a design process and design tools.

Flexibility in Process

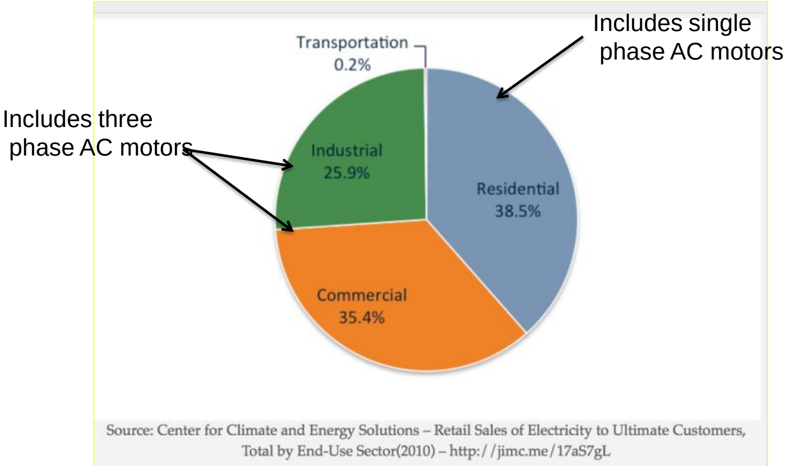
From the Science Photo Library

The development of small AC drives allowed flexibility in the design of factory processes

Electrical Machines

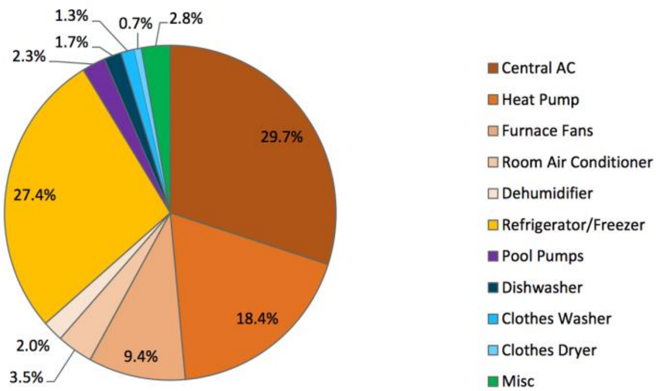
How did we get from there to here?

Primary Electrical Energy Consumption by End Use Sector



Courtesy of Dr. J. Hendershot

Residential Motor-Driven energy distribution = $1.3*10^{12}$ KWh



December 2013

Courtesy of Dr. J. Hendershot

Scientific Knowledge versus Industrial Needs

- Scientific Knowledge provides information on the characteristics of a particular domain
  – The laws of physics relating to electromagnetic phenomena
  – The behaviour of materials
  – The interactions with, and impacts on, other domains
  – ….

Scientific Knowledge versus Industrial Needs

- The creation of a manufacturable device requires:
  – A knowledge of issues impacting device performance
  – An understanding of how the device is to be manufactured
  – An estimation of the requirements of the marketplace
  – A recognition of the current state of technology and scientific knowledge

Industrial Needs versus Scientific Knowledge

- The development of electrical machines since 1821 has required both of these
  - Development has been significant from an industrial viewpoint
  - Advances have occurred from an academic, scientific perspective
  - BUT
    - How well are these two linked?
    - Let's explore and find out….

Scientific Knowledge versus Industrial Needs

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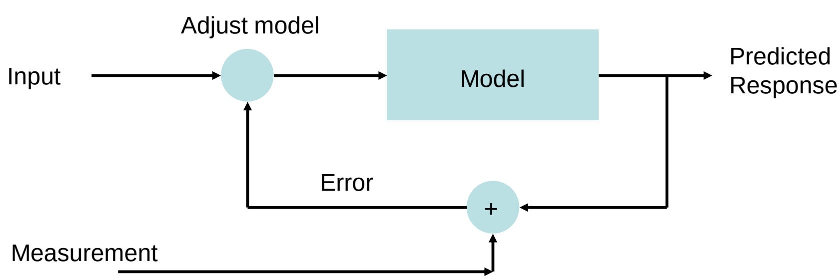
The Development of Models

- "Humans are model builders"
  - Humans need models to:
    - Predict system behaviour
    - Control system behaviour
    - Modify their environments
    - Function socially
  - A model provides a representation of a particular system *and helps visualize its performance.*

The Development of Models

- Model development is based on the physics, information, knowledge and comparisons with the real world



The Development of Models

- "Humans are model builders"
  - A model is "correct" if it represents the device performance with the level of accuracy desired
  - A model is fundamental to being able to design

Properties of Models

- A model embeds an understanding (knowledge) of the system being studied. This can be
  - objective
  - subjective
- A model can be
  - A physical analogue – e.g. a "scale model", Maxwell's fluids analogy
  - A virtual representation – e.g. a thought model.
- Models involve a variety of levels of approximation – reflect the state of knowledge

Physical Modeling

- A scale model device

Properties of Models

- Models are frequently partial
  - Some aspects of system behaviour are not considered
  - The representation concentrates on one "attribute" or property.
  - A balance between what is known and what is needed
- The goal of science is to provide the knowledge on which to base ever more comprehensive models.

1. The Age of Discovery

From zero to 1820

History I

- The ancient Chinese recognized that magnetised arrows would point north… - over 2000 years ago.
- If an iron needle was stroked with a "loadstone" (a naturally occurring magnetic ore), it would become "magnetized".
- Placing the needle in a piece of straw and floating it in water created the first compass.

History II

- The compass was used to orient buildings, tombs and furniture.
- There is evidence that it was used for navigation in the 6th Century BC – the first reference is in 83 AD.
- By 800-1000 AD, Vikings were using the compass for their long navigations.
- *The compass is a simple magneto-mechanical actuator*.

History III

- Peter Peregrinus (1269) described the concept of “poles”
  - A magnet had two
    - one seeking the north pole of the earth
    - the other the south pole
  - Like poles repelled each other

History IV

- Around 600 BC, electrostatic effects were recognized.
- In 1650, Otto van Guericke created an electric generator using a sulphur ball rubbed by a pad.
- Electrostatic forces were measured in 1785 by Coulomb.
  - The inverse square law for electrostatic force.

$$F = \frac{kQ_1Q_2}{d^2}$$

History V

- In 1799 Volta produced the first battery and thus provided a source of electric current.
  - (There is some evidence that batteries may have existed around 2000 years ago ..)
  - This enabled the study of moving charges…
    - A critical development

2. Theory & Experiment – 1820+

The age of experimentation and heuristics…

Oersted 1820

- The birth of electromagnetism
  - 1820 – a current through a wire causes a compass needle to deflect
  - *The first electromagnetic actuator!*

Hans Christian Oersted

Ampere 1820

- In 1820, following Oersted’s discovery that a current caused a magnetic field, Ampere defined the relationship between electric flow and the magnetic field produced.

Andre-Marie Ampere

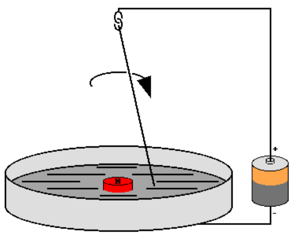
$$I = \oint H.dl$$

Ohm 1825

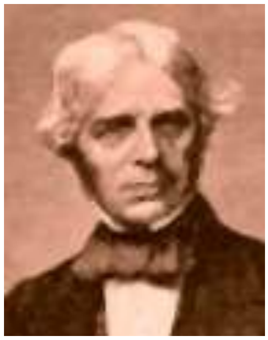
- Cavendish worked out a qualitative relationship between voltage and current but his results were not known until Maxwell published them in 1879!
- Ohm performed the resistance work in 1825 and 1826 and published in 1827…
- Kirchhoff produced his circuit laws in 1847 (while still a student!).

Faraday 1831

- In 18~~2~~31 Faraday created the first electric motor.



Michael Faraday



Faraday 1831

- A changing magnetic field induced a voltage in a coil

$$v = -N\frac{d\varphi}{dt}$$

So.. By 1850 all the background used today for equivalent circuits was in place but an all encompassing theory was still missing..

Pixii 1832

- 1832 – the first direct current dynamo..
  - Hippolyte Pixii
    - The inventor of the commutator
- Used, eventually, as a telephone bell ringer.

Maxwell - 1855

- Faraday's Lines of Force..
  - "No electrical theory can now be put forth, unless it shews the connexion not only between electricity at rest and current electricity, but between the attractions and inductive effects of electricity in both states.."
  - "The student must make himself familiar with a considerable body of the most intricate mathematics, the mere retention of which in the memory materially interferes with further progress."

Maxwell - 1855 (cont'd)

- "The first process in the effectual study of the science must be one of simplification and reduction of the results to a form in which the mind can grasp them. The results of this simplification may take the form of a purely mathematical formula or of a physical hypothesis."
- "In the first case we entirely lose sight of the phenomena to be explained… By adopting a physical hypothesis, we see the phenomena only through a medium, and are liable to that blindness to facts and rashness in assumption which a partial explanation encourages"

Maxwell - 1864

- "A Dynamical Theory of the Electromagnetic Field"
  - Creates 20 equations involving 20 variable quantities..
  - Expressed in terms of quaternions…

Maxwell - 1873

- The equations were still expressed in quaternions in the Treatise of 1873..(Art 619)
  - However, he was pressured into rewriting them in terms of vectors – a task which was about 80% complete on his death. The work was subsequently completed by Heaviside to produce the four vector equations we use today.
- The treatise also expressed the concept of surface forces (or stresses) based on the electromagnetic field in Art 642 – this is the basis for most modern force calculation algorithms!
- Art 446 mentions work of Weber (1852) in non-linear magnetization characteristics.

Finally – the Equations of the Electromagnetic Field

- Maxwell-Heaviside Equations

$$curl\, H = J + \frac{\partial D}{\partial t}$$

$$curl\, E = -\frac{\partial B}{\partial t}$$

$$div\, B = 0$$

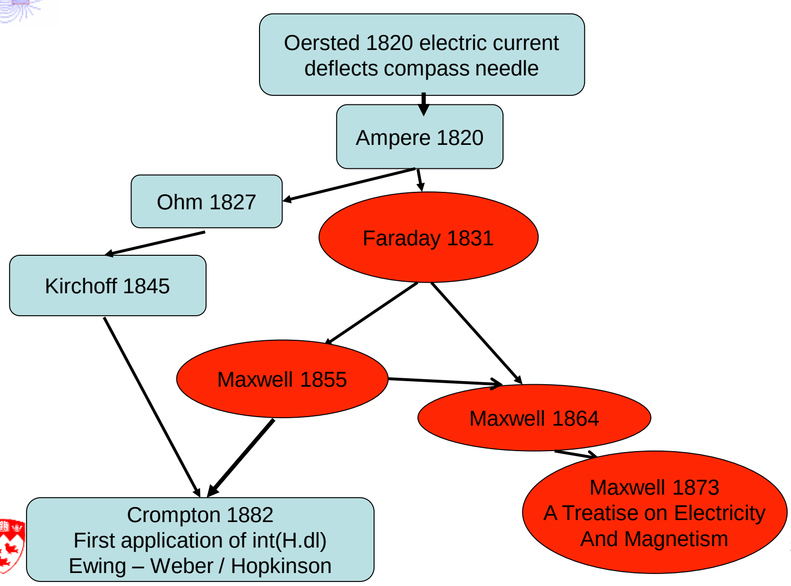
$$div\, D = \rho$$

The differential versions of Ampere and Faraday
Added ∂D/∂t – critical…

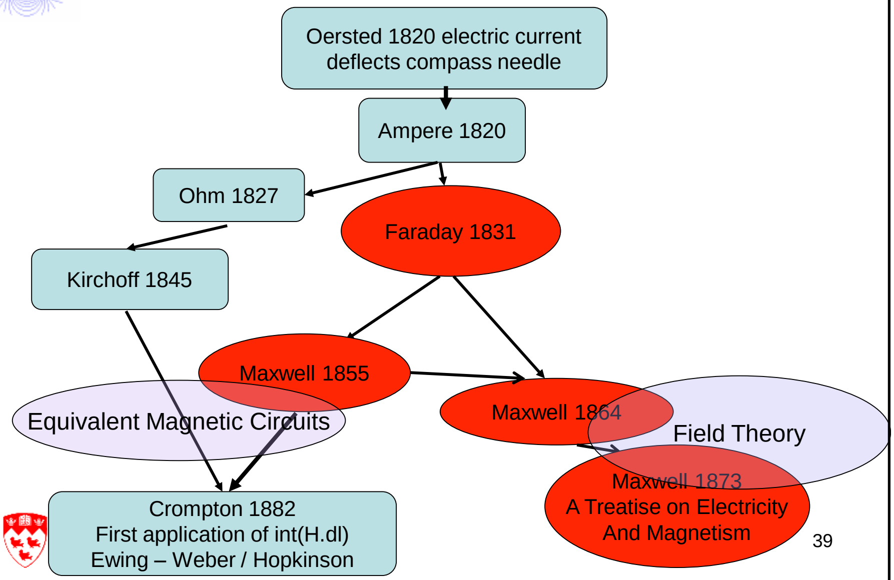
Key Issues in Magnetic Devices

- Drop the ∂D/∂t term – not needed for low frequency…
- Maxwell Stresses provide a force computation mechanism that was unrecognized until the mid 1950's (Carpenter)
- Two independent analysis/design approaches:
  - Equivalent magnetic circuits vs Field Theory
    - These two represent the two paradigms discussed by Maxwell in 1864..

The Development of Understanding



The Development of Analysis



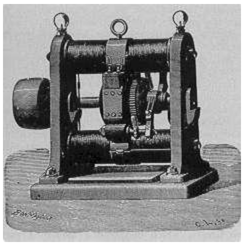
- So.. In a period of 45 years from Oersted to Maxwell, the basic theory of electromagnetism, as we know it today, was constructed.
- In parallel – largely independent of the theory - devices based on the experimental work were constructed and the development of industrial power, transmission, applications began.

Magnetic Device Development in the 19th Century

- Oersted accidentally created the first actuator!
- Electric motors – the ancestors of today's devices – existed from the 1820's..
- As a result of Davenport's experimentation with the electric motor, Moses G. Farmer of Massachusetts bolted an electric motor onto a carriage in 1847 and became the first unofficial electric car builder. Farmer's electric carriage was powered by 48 Grove cells and could carry two people.

History (cont'd)

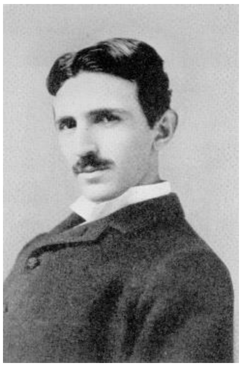
- In 1873, by accident, two Gramme dynamos were connected together …
  - When the first was rotated by a steam engine, the second rotated backwards as a motor.
    - The first demonstration of mechanical power transmission through electrical means



History (cont'd)

- 1888
  - The induction machine was developed when Tesla suggested removing the commutators…
  - The ancestors of almost all modern electromechanical devices existed.

Nicola Tesla



So – by 1880 electrical power was serving society but…

- Analysis by Lumped Parameters:
  - Crompton – 1882 figured out what Ampere meant - pressure (voltage) proportional to coil current/ 2 times airgap – assume magnetic materials are perfect.
- So – understanding grows but the ability to use this in models was restricted.

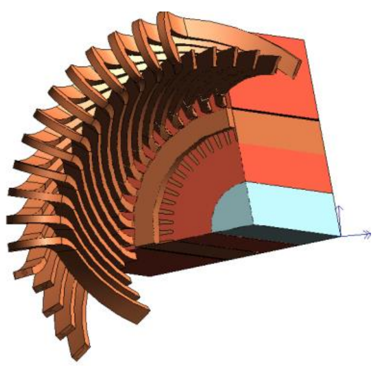
3. The Age of Calculation – 1880+.

Complex Geometries and Materials

Problem:

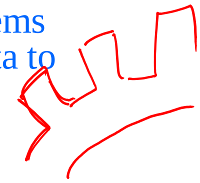
The geometries needed are extremely complex.
The materials are non-linear…

Analysis methods did not exist to solve the full problem.



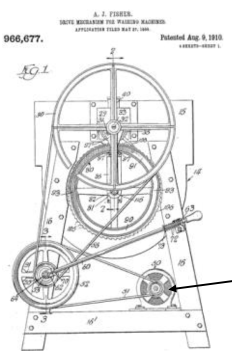
Sub-problem Analysis

- Step 1 – ignore iron… only work with air gap fields..
  - Doesn't take into account field leakage, power losses in iron, fringing, etc.
- Step 2 – add simple sub-problem analyses – find parts of the device where Maxwell's equations can be solved – e.g. the tooth/slot region – the work of Carter in generating design tables.
  - Embed this information in the equivalent circuit
- Step 3 – combine several simple subproblems (algebraic solutions) with experimental data to improve circuit representations.



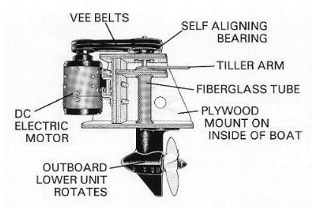
A Need for Effective Design Tools

- Electric devices become more common in the home:



Washing machine in 1910

Electric motor



Electric Drive for Boats around 1910

A Need for Effective Design Tools

- Magnetic saturation causes loss in performance
- Higher efficiencies become important
- More power from a given size…
- Reduction in cost…
- All these issues add pressure to the need to provide more accurate simulation tools (and the potential of Maxwell's Equations to help is seen but it is out of reach..)

The Analysis Problem

- Solving the equations directly
  - Not possible for general geometries
  - Simplified pieces only:
    - Subdivide problem into simpler structures which can be analysed algebraically
    - Use heuristics to determine the subdivisions

The Analysis Problem (cont'd)

- Over the past century developments have included:
  - Conformal mapping (potentials)
  - Equivalent Circuits (mmf, flux…integral terms)
  - Complex algebraic solutions for a range of practical problems (potentials)
- All of these have been developed to a high degree and can provide detailed information on aspects of device performance.

The Analysis Problem (cont'd)

- Analogue systems can be used to generate solutions to field problems:
  - conducting paper (Teledeltos), electrolytic tanks, rubber sheets, hand sketching (curvilinear squares)..
- Finite differences – hand relaxation techniques – 20 by 20?
- In 1915, Galerkin published the theory of finite elements for PDE's but there was no practical implementation..

The Analysis Problem (cont'd)

- So..
- For almost 80 years from Maxwell's treatise
  - Algebraic systems provided models of device behaviour.
  - Heuristics, i.e. experience and design knowledge, provided the basic design tools.
- Laboratory experiments and previous designs were the foundations of model development and new designs.

The Analysis Problem (cont'd)

- An expensive approach!
- Any major advances in technology might invalidate previous knowledge and experience.
- Design development is strictly evolutionary
  - Small changes
  - Push the boundaries slowly…

Solving the Equations

- Direct solution of the field equations could be accomplished for small "simple" problems
  - through Finite Difference approximations
    - Could be done by hand for small models
    - A process of repeating a small set of calculations a very large number of times
  - Or through direct integration
    - Algebraic methods for "simple" geometries
    - Numerical approaches for more complex systems

4. The Age of Computational Electromagnetics – 1940+

Solving the Equations – for potentials

- The development of the digital computer provides an opportunity to:
  - automate the previous "numerical" methods.
  - Make some design decisions (through design sheets) automatically.
- Thus two branches of development.
- Leads to the concept of *Computational Electromagnetics…*

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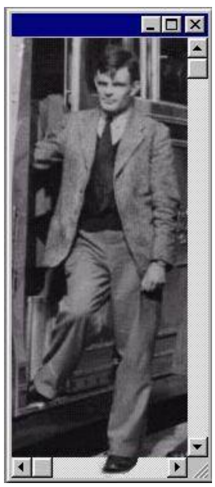
Computer Development

- 1936 – Alan Turing conceives a "universal machine"
  - This machine can be programmed to duplicate the function of any other machine.



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Computer Development - ENIAC

- 1947 – US Patent filed for ENIAC:

"…With the advent of everyday use of elaborate calculations, speed has become paramount to such a high degree that there is no machine on the market today capable of satisfying the full demand of modern computational methods. The most advanced machines have greatly reduced the time required for arriving at solutions to problems which might have required months or days by older procedures. This advance, however, is not adequate for many problems encountered in modern scientific work and the present invention is intended to reduce to seconds such lengthy computations..."

Computer Development - ENIAC

- Created in February 1946
  - 5000 adds, 300 multiplies per second (compare a modern microprocessor at approximately 1 billion adds per second)
  - Programmable
  - 200 bytes (equivalent)
- Turned off in October 1955
  - By this time it is estimated that it had completed more arithmetic computations than had been done by the entire human race up to 1946!

Computer Development (cont'd)

- 1955 – IBM 702:
  - 4000 adds per second,
  - 800 multiplies per second,
  - CRT storage system giving 10 kilobytes of storage,
  - 40 k bytes per second from memory,
  - 15k bytes per second from magnetic tape.
- 1956 - Veinott publishes paper on using a computer for machine design

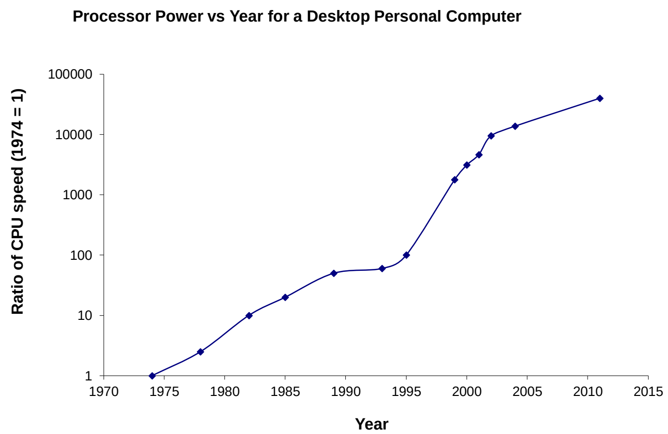
Desktop Computational Power

- 1971, Intel produce the 4004
  - 4 bit cpu
  - 2 kbits of ROM
  - 320 bit RAM
- 1974 – the 8080
  - 2 MHz processor
  - 16 bit address, 8 bit data
  - Up to 64 kbytes of RAM

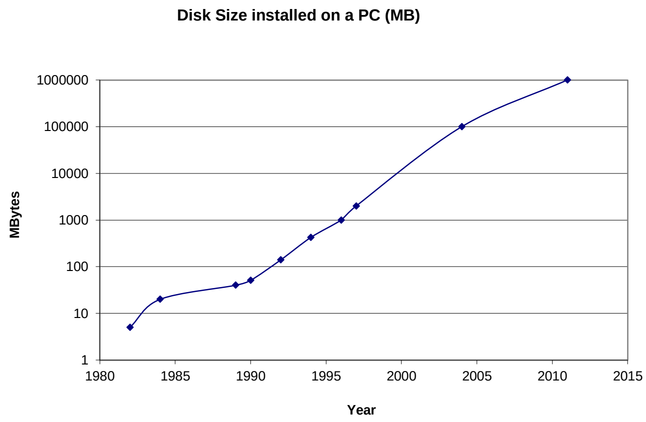
Desktop Computational Power (cont'd)

- 1981 – the IBM PC
  - Based on the 8088
  - Changed to the 80286 in 1982 – a 16 bit processor – capable of serious numerical analysis.

Desktop Computational Power (cont'd)



Desktop Computational Power (cont'd)



Desktop Computational Power (cont'd)

- Processor speed
  - Growing at about 40% per year
- Installed memory sizes
  - Growing at about 40% per year
- Installed disk size
  - Growing at about 60% per year
- Data transfer rates on LANs
  - 10 Mbits/sec in 1990, 1000 Mbits/sec in 2004, 1Gbit/sec in 2010 – a little less than 40% per year

Computational Electromagnetics

- So, with the growth in computational power,
  - What can we do?
  - What should we do?
- Three questions drive the development of models
  - Can we solve the problem and obtain *sufficiently accurate* answers?
  - Can the problem be solved more efficiently?
  - What do we really need to model?

Computational Electromagnetics (cont'd)

- Can we solve the problem?
  - Is the appropriate mathematical background in place?
  - Is the computational machinery powerful enough?
- Can we solve the problem more efficiently?
  - Are there algorithms/representations which either
    - Have a reduced complexity
    - Reduce problem size for the same accuracy

Computational Electromagnetics (cont'd)

- The goal is to create an accurate simulation of reality
- Increases in computer capability are used to create a virtual world – the VIRTUAL LABORATORY