ELEC 621
Numerical Techniques in Electromagnetics

Lecture 1 General Info and Theoretical Foundations

Wolfgang J.R. Hoefer

Computational Electromagnetics
Research Laboratory
University of Victoria, Canada

Objectives

1. Meet the students, get their names and addresses, discuss modalities, assessment, etc.
2. Introduce course philosophy and content. Show course webpage. Give references.
3. Explain significance of electromagnetic modeling in modern CAD design. Stress the importance of modeling both in frequency and time domains.
4. Compare traditional and alternative approaches to modeling. Discuss challenges and limitations.
5. Introduce students to the general methodology for field analysis, the classification, and the general features common to all field modeling methods.
6. Discuss frequency domain vs. time domain concepts.

Wolfgang J. R. Hoefer ELEC 621 Numerical Techniques in Electromagnetics Lecture 1 - 1

Lecture Structure

I. Introduction, motivation and historical perspective

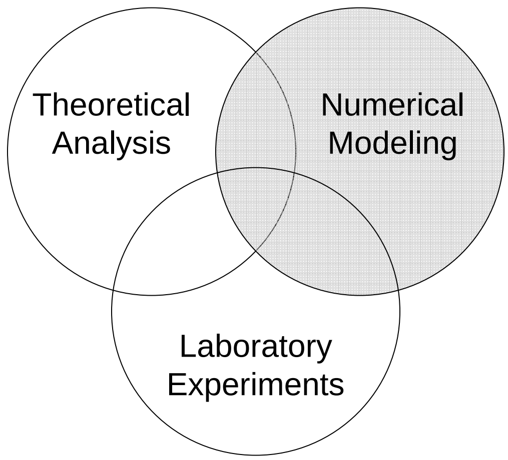
1. Importance of numerical modeling.
2. Driving forces in field modeling.
3. Why computers are needed in modern electromagnetic design. Understanding CAD.
4. Functions performed by CAD programs. Traditional and alternative solution of electromagnetic problems.
5. Methods for solving electromagnetic problems.
6. Classification of methods and their general properties.
7. Frequency vs. time domain concepts.

Access to the Course page

http://www.ece.uvic.ca/~whoefer

All documents for distribution to the class will be posted on the course page. Check periodically.

Introduction



The Three Pillars of Electromagnetic Microwave and Lightwave Engineering

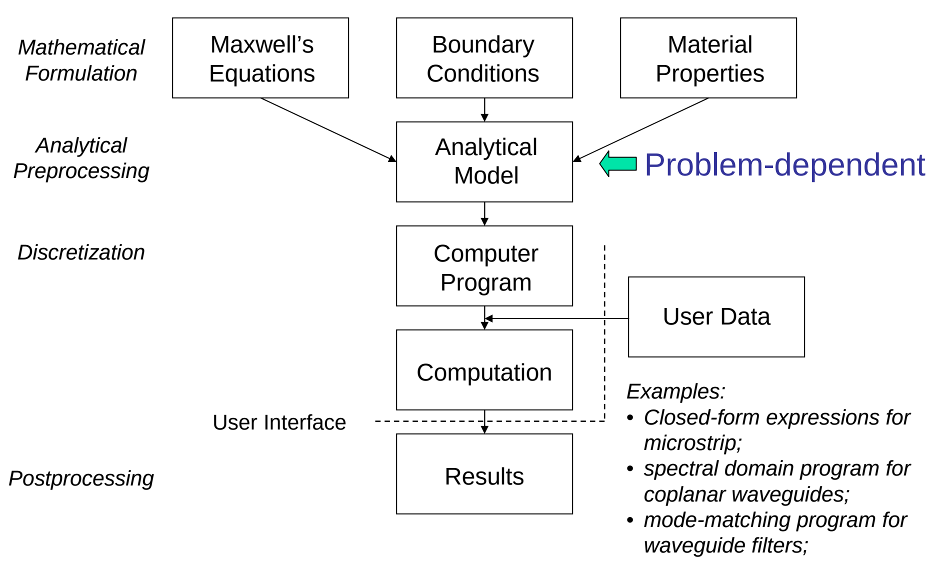
Importance of Numerical Modeling

- Key to analysis, design and optimization of r.f. to optical systems.
- Basis for field-theory based and process-oriented CAD.
- Key to economical success of a product through shortening of development time.
- Only means for dealing with complex electromagnetic structures.
- Suitable for creating CAD tools and expert systems.
- Theoretical models must be validated by experiments. Theoretical and experimental work are of equal importance.

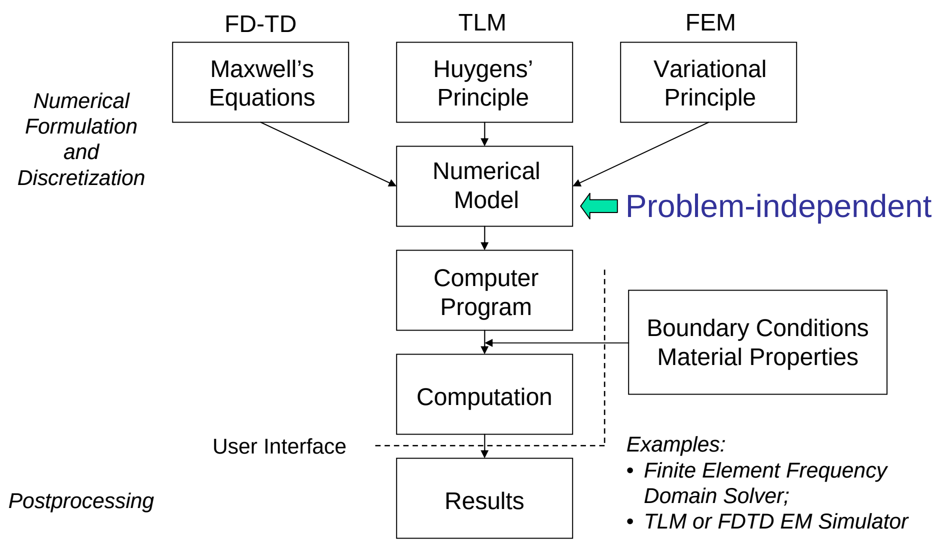
What Drives Field Modeling ?

Driving Forces in Field Modeling	Examples
Hardware Availability:	
• Computers with large memory and clock rates	Workstations, Supercomputers
• Vector and parallel processors	Parallel Processors
Structures and processes to be modeled:	
• Circuits of high complexity and density	Monolithic circuits, interconnects
• Impulsive waveforms and transients	High speed digital/mixed signal circuits
• Nonlinear and time effects	Solid state devices, superconductors
• EMI/EMC and crosstalk effects	High speed logic and communication
• Packaging effects and signal integrity	MW and mmW Integrated Circuits
Requirements of Designers and Users:	
• User-friendly interface with modeling tool	Geometry and process-oriented tools
• Flexibility and versatility of modeling tool	EM Simulators, multi-level simulation
• Field visualization and animation	Dynamic 3D graphics, color maps
• Engineering parameter extraction	S-parameters from field solutions

Classic Electromagnetic Solution

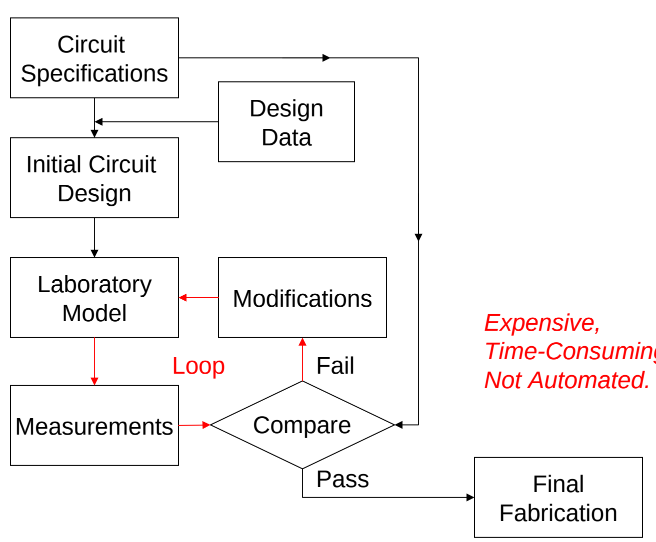


Modern Electromagnetic Solution



Wolfgang J. R. Hoefer ELEC 621 Numerical Techniques in Electromagnetics Lecture 1 - 8

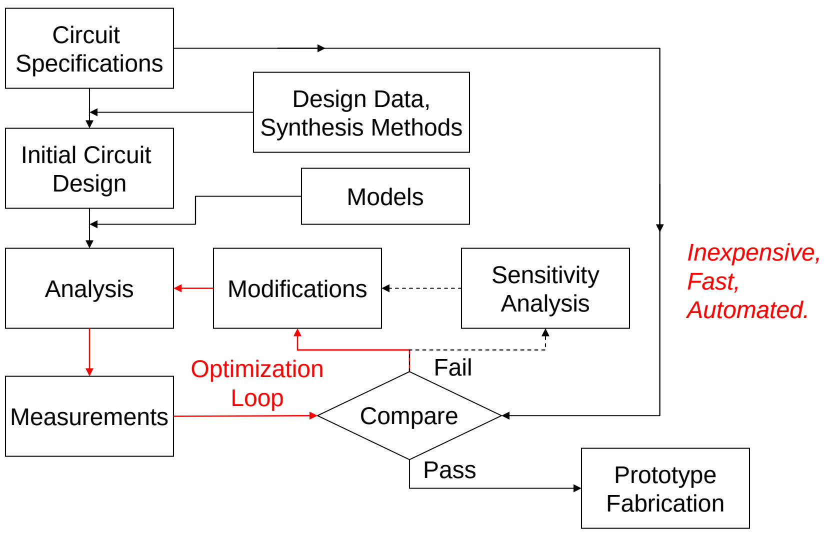
Conventional Microwave Design



Expensive,
Time-Consuming,
Not Automated.

Wolfgang J. R. Hoefer ELEC 621 Numerical Techniques in Electromagnetics Lecture 1 - 9

Computer-Aided Design (CAD)



CAD Functions

- Planning
- Synthesis
- Partitioning
- Modeling
- Simulation
- Layout
- Verification
- Testing
- Documentation
- Inventory
- Etc…

Electromagnetic Simulators

- An Electromagnetic Simulator is a field modeling tool that
  - solves electromagnetic field problems by numerical analysis;
  - extracts engineering parameters from the field solution and visualize fields and parameters;
  - allows design by means of analysis combined with optimization.
- The field solver engine employs one or several numerical methods obtained through the practice of Numerical Electromagnetics.

Numerical Electromagnetics (NE)

- Numerical Electromagnetics is the theory and practice of solving electromagnetic field problems on digital computers;
- It provides the only viable approach to solving “real world” field problems;
- It enables Computer-Aided Engineering (CAE) and Computer-Aided Design (CAD) of electromagnetic components and systems.

Models of Light Propagation 1

- **Pythagoras 6th century B.C.**
  Light is a stream of particles emitted from a source of light.
- **Demokritos 460-370 B.C.**
  All objects consist of a large number of particles: the atoms. Images are transmitted by atoms detaching themselves from the surface of objects and drifting through space.
- **Aristotle 384-322 B.C.**
  Light moves as a wave, like ripples on the water.
- **Newton 1662-1727**
  Light is made up of tiny particles (corpuscules) that fly through space.

Models of Light Propagation 2

- **Huygens 1629-1695**
  Light is transmitted in the form of shock waves made up by the superposition and succession of elementary spherical disturbances of the Ether (Huygens' Principle).
- **Maxwell 1831-1879**
  Light is an electromagnetic wave governed by the interaction of electric and magnetic fields (Maxwell's Theory, experimentally confirmed by Hertz).
- **Einstein/de Broglie 20th Century**
  Light has both particle and wave properties. These aspects are complementary. One or the other dominates, depending on the phenomenon under study.

Solving EM Field Problems

- Find electromagnetic field and/or source functions such that they
  - obey Maxwell's equations,
  - satisfy all boundary conditions,
  - satisfy all interface and material conditions,
  - satisfy all excitation conditions.

  (in both time and space, or at one freq. in space)
- The solution is generally unique (Analysis)

Field-Solving Methods

Methods for solving Maxwell's Equations:

- Analytical Methods

  Exact explicit solutions (only a few ideal cases)
- Semi-Analytical Methods

  Explicit solutions requiring final numerical evaluation
- Numerical Methods

  Differential or integral equations are transformed into matrix equations by projective approximations and solved iteratively or by matrix inversion

Classification of Methods 1

Frequency Domain Methods (Time-Harmonic) ⟶ Fourier Transform ⟵ Time Domain Methods (Transient)

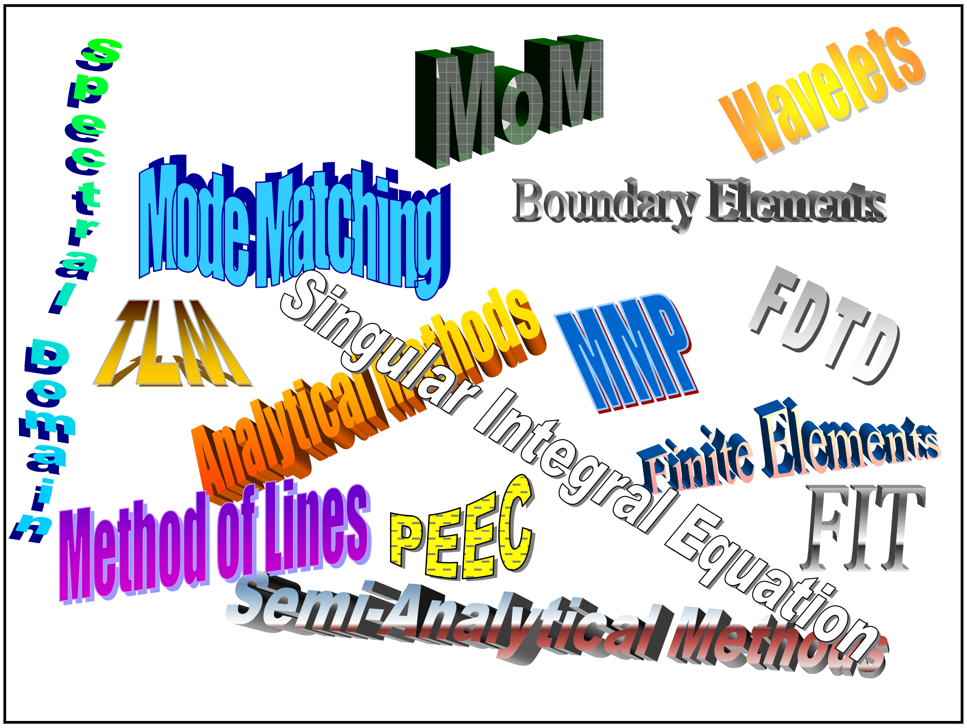
This distinction is based more on human experience than on physical or mathematical considerations.

The time dimension can be treated as a fourth dimension in Minkowski space in the form jct, where c is the speed of light.

In the most general sense, solution methods can thus be classified according to the number of dimensions upon which the field and source functions depend.

Classification of Methods 2

1D Methods:	Fields and voltage/current vary in one space dimension (Transmission Line Problems) (…Touchstone, Supercompact, SPICE….)
2D Methods:	Fields and currents vary in two space dimensions (Cross-section problems, TE_{n0} waveguide problems) (….FEM-2D, MEFiSTo-2D….)
2 1/2 D Methods:	Fields vary in three space dimensions, currents vary in two space dimensions (Planar multilayer circuits) (…Sonnet, Momentum, Ensemble ….) frequency domain
3D Methods:	Fields and currents vary in three space dimensions (General propagation, scatter-ing and radiation problems) (…HFSS, FEGS, MEFiSTo-3D, CST, Quickwave..)



What have all Methods in Common ?

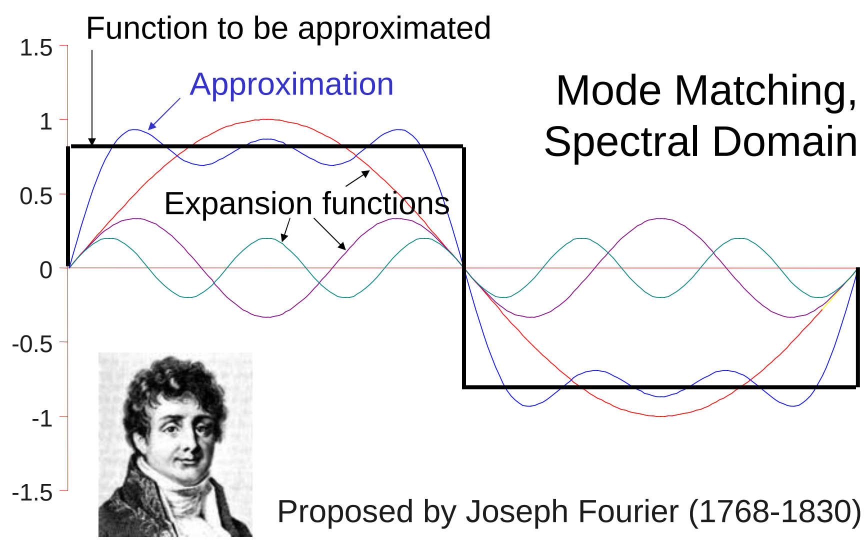
1. In all methods, the *unknown* solution is expressed as a sum of *known* functions (*expansion* functions or *basis* functions).
2. The *weight* (coefficient) of each expansion function is determined for best fit.

What distinguishes them?

- the electromagnetic quantity approximated,
- the expansion functions used,
- the strategy employed for determining the coefficients of the expansion functions.

Wolfgang J. R. Hoefer ELEC 621 Numerical Techniques in Electromagnetics Lecture 1 - 21

Full-Domain Expansion Functions

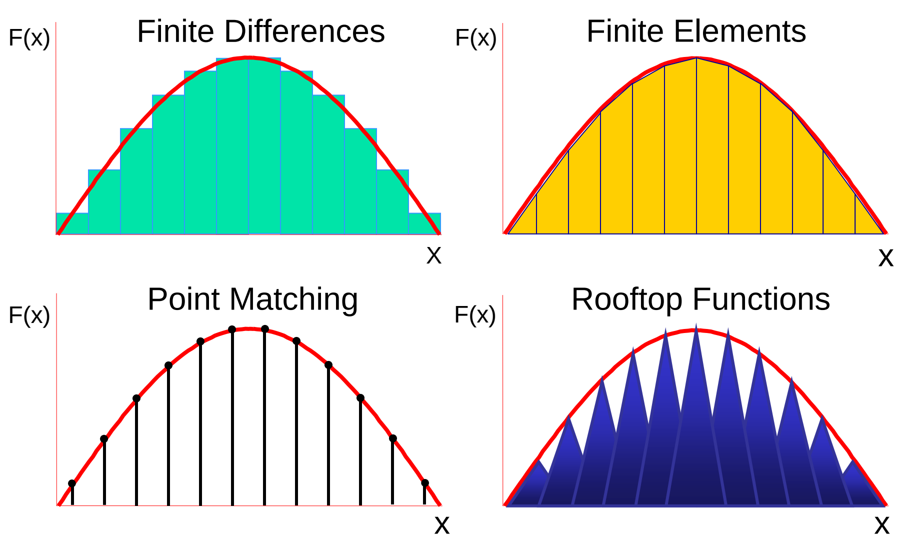


Mode Matching, Spectral Domain

Proposed by Joseph Fourier (1768-1830)

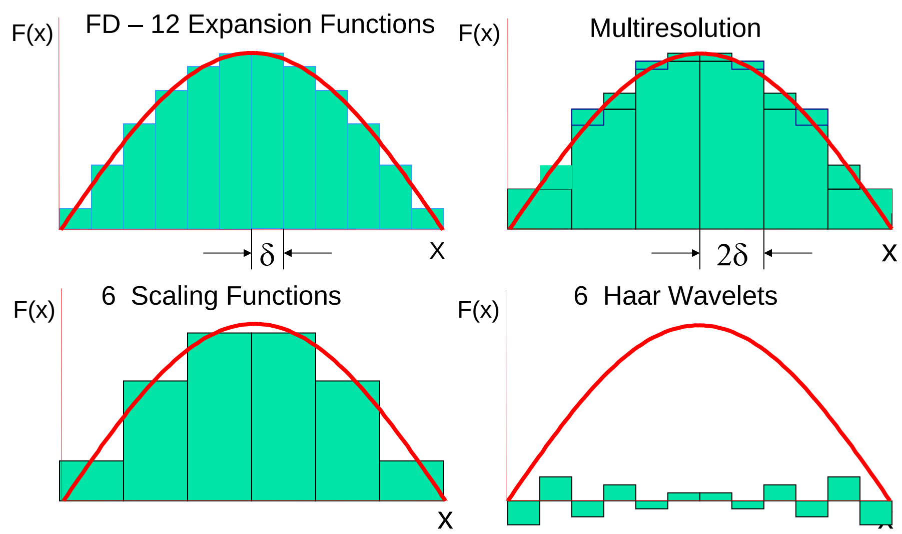
Wolfgang J. R. Hoefer ELEC 621 Numerical Techniques in Electromagnetics Lecture 1 - 22

Subsectional Expansion Functions



Wolfgang J. R. Hoefer ELEC 621 Numerical Techniques in Electromagnetics Lecture 1 - 23

Multiresolution with Haar Wavelets



Wolfgang J. R. Hoefer ELEC 621 Numerical Techniques in Electromagnetics Lecture 1 - 24

Frequency and Time Domain Concepts

- Complex Frequency
- Phase angle
- Complex Dielectric Constant
- Complex Reflection/ Transmission Coeff.
- Complex Impedance
- Q-Factor
- Complex multiplication

- Time dependence
- Delay
- Real permittivity and conductivity
- Reflection/Transmis-sion time response
- Impulse response
- Decay time
- Time domain convolution

Wolfgang J. R. Hoefer ELEC 621 Numerical Techniques in Electromagnetics Lecture 1 - 25

Why model in the frequency domain?

- Most microwave engineers are more familiar with FD concepts than with TD concepts,
- Frequency domain simulations are steady-state,
- Complex notation is elegant and efficient,
- Specifications are traditionally formulated in the FD (S-Parameters, loss tangent, dispersion),
- Time domain information can be obtained by inverse Fourier Transform (Causality issues!),
- Dispersive materials and boundaries are easily described by frequency-dependent parameters.

Wolfgang J. R. Hoefer ELEC 621 Numerical Techniques in Electromagnetics Lecture 1 - 26

Why model in the time domain?

- Time domain simulations are life-like
- Virtual experiments are set up as in the lab (Source, reference planes, output probes)
- Cause and effect can be distinguished
- One simulation can cover a wide bandwidth
- Transient phenomena can be simulated
- Nonlinear behavior is modeled naturally
- Dispersive materials and boundaries are modeled in a more physical manner

Wolfgang J. R. Hoefer ELEC 621 Numerical Techniques in Electromagnetics Lecture 1 - 27

Summary and Conclusions

- Numerical Methods allow us to solve real life electromagnetic problems. They form the engine of electromagnetic simulators.
- Electromagnetic simulators are not merely Maxwell equation solvers, but powerful simulation and design tools with visualization capabilities.
- Understanding the underlying numerical methods is essential in assessing the accuracy, performance and limitations of a particular simulation tool.
- Electromagnetic simulators are the heart of modern CAD tools for analog microwave, digital high-speed and mixed signal design, EMC and signal integrity engineering and other applications of electromagnetic fields and waves.