A Survey on Algorithms for Big Data Analysis in Electromagnetics Scattering Problems

InfoSys 2021 Congress

The Thirteenth International Conference on Advances in Databases, Knowledge, and Data Applications

May 30, 2021 - June 03, 2021 - Valencia, Spain

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Education

- Ph.D. student in Electrical Engineering, Howard University, USA.
- Master of Engineering (M.Eng.), Howard University, USA (2019).
- B.S. Electrical Engineering, Ana G. Mendez University, Puerto Rico (2016).

Recent Professional Experience

- Graduate Research Engineer Intern, Massachusetts Institute of Technology Lincoln Laboratory, USA (2021).
- Research Fellow, Howard University, USA (2019-2021).
- Research Fellow, Tsinghua University, China, (2019).
- Graduate Research Engineer Intern, The Johns Hopkins University Applied Physics Laboratory, USA (2018).

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Research Interest

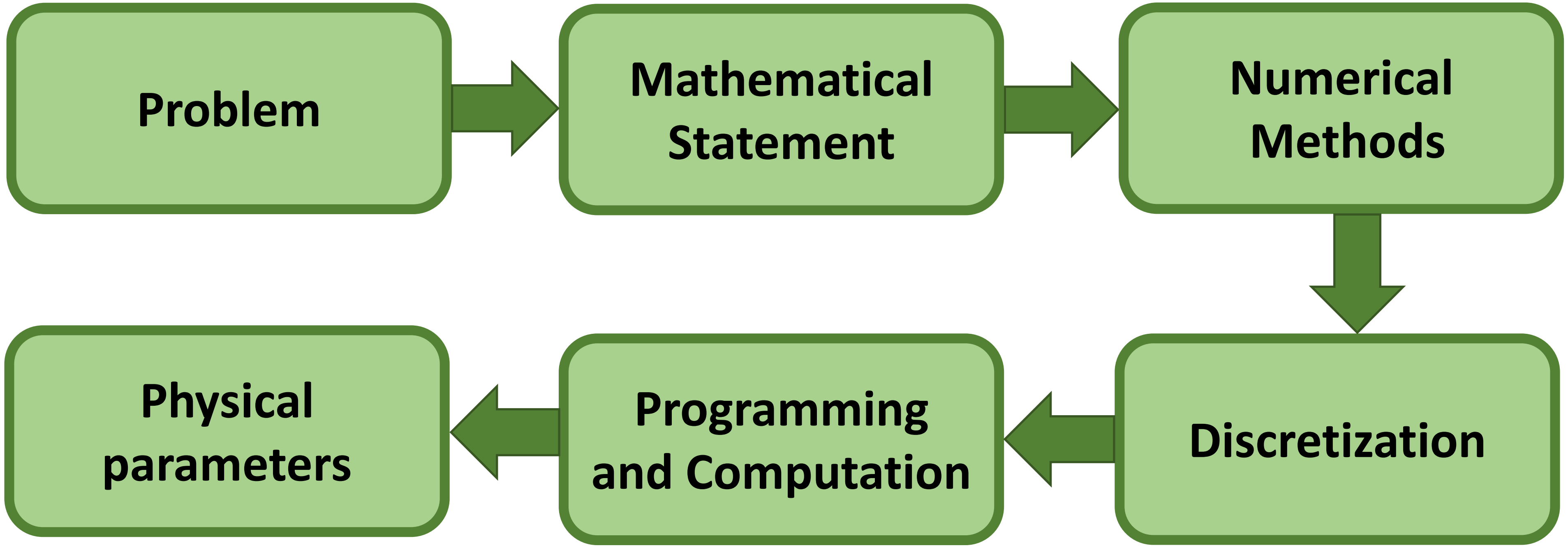
- **Applied and Computational Electromagnetics**
  - Modeling and Simulation of Electromagnetic Scattering.
  - Advanced Numerical Methods, especially Integral-equation-based methods.
  - Fast Algorithms and Preconditioning Techniques.
  - Large-scale Parallel Computing Techniques.
- **Machine Learning and Data Analytics**
  - Inductive Machine Reasoning.
  - Decision Making and Intelligent System.
  - Information Entropy Minimax Principle.
  - Laplace-statistic-based Trend Analysis.

Outline

- Big Data
- Computational Electromagnetics
- Method of Moments in Integral Equations
- Fast Multipole Method
- Multilevel Fast Multipole Method
- Big Data Techniques in Electromagnetic Engineering Problems

Computational Electromagnetics (CEM)

Computational electromagnetic (CEM) is the research area for developing and investigating numerical methods and techniques for the modeling and simulation of electromagnetic (EM) problems.



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CEM: An Interdisciplinary Research Area

Physics

- EM Theory and Principles
- Maxwell's Equations
- Green's Functions
- Wave Equation
- …

Computer Science

- Data Structure
- Computability & Complexity
- Parallel Programming
- …

Mathematics

- Linear Algebra
- Numerical Methods
- Vector Analysis
- Partial Differential Equations
- …

Computational Electromagnetics

- ❖ Advanced Engineering Application
- ❖ Efficient and Accurate Problem Solutions

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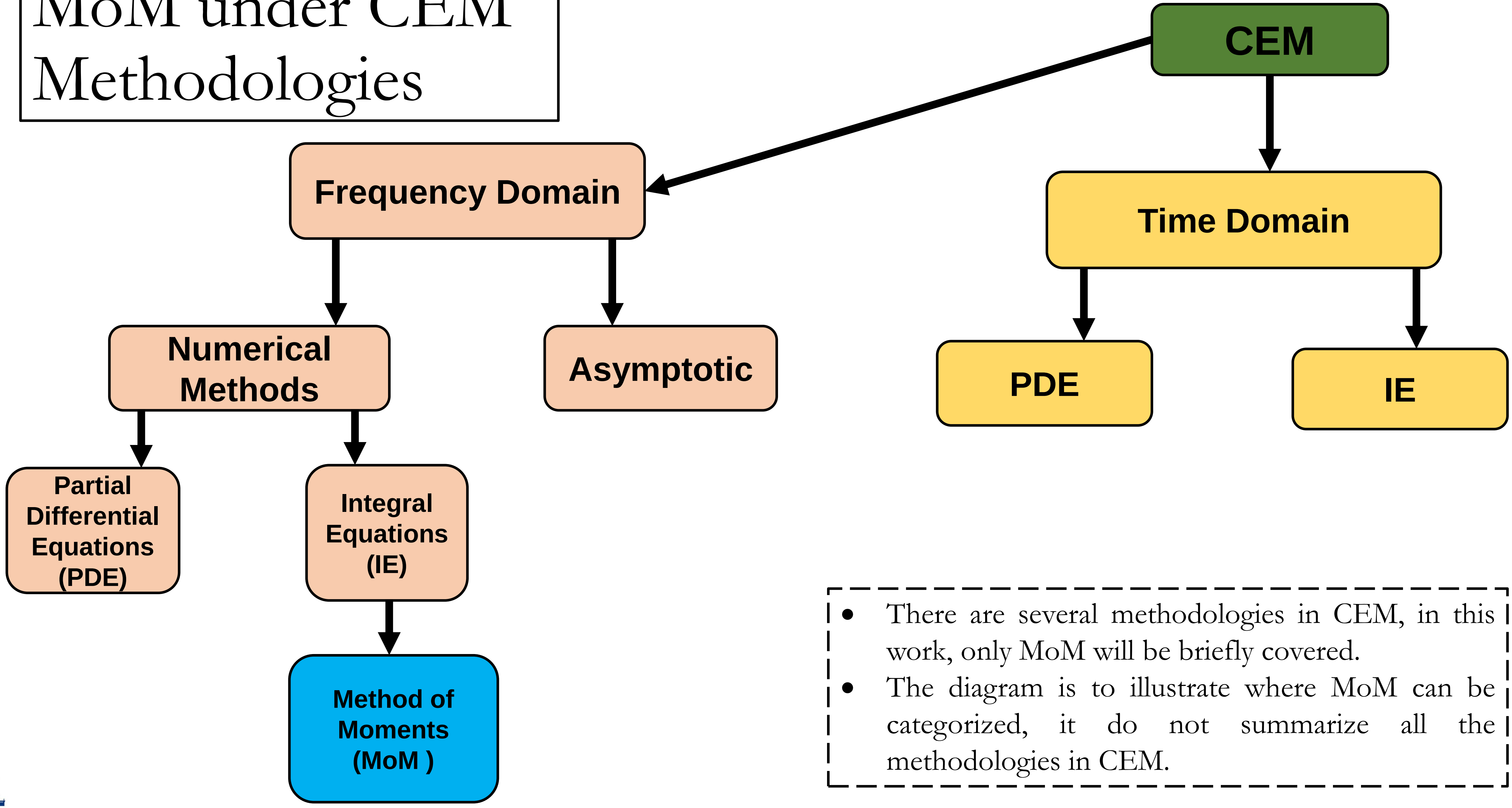
MoM under CEM Methodologies



- There are several methodologies in CEM, in this work, only MoM will be briefly covered.
- The diagram is to illustrate where MoM can be categorized, it do not summarize all the methodologies in CEM.

Rudimentary Steps in CEM Modeling and Simulation

- Identify Engineering or Scientific Problem to Solve.
  - Example: Compute Electromagnetic Signature of a Target Object.
- Physical Modeling.
  - Through Physics, Describe the Problem Mathematically.
  - Examples, Integral Equations, such as EFIE, MFIE, or CFIE.
- Geometrical Modeling.
  - Design and Discretization of Object to be Study.

Continue

- Numerical Modeling.
  - Solve the problem by Numerical Methods.
  - Example, Method of Moments.
- High Performance Computing.
  - Example, Large-scale Parallel Computing, Domain Decomposition Methods, Dynamically h-,p- and hp-algorithms in Time Domain.
- Final Evaluation and Prediction.
  - Example, Radar Cross Section.

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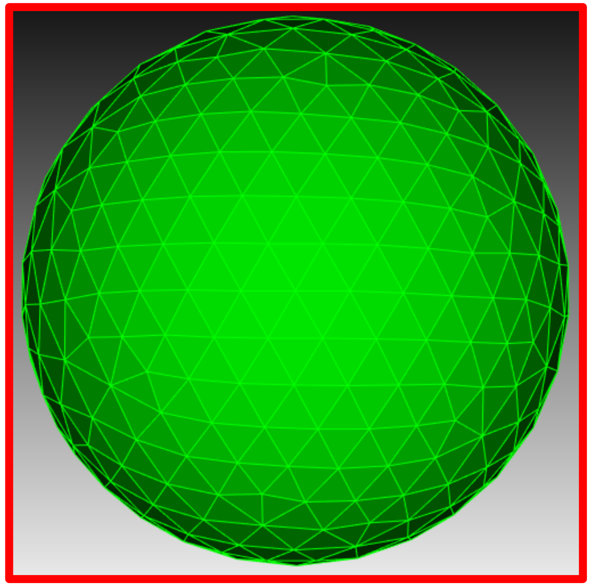
Method of Moments in Integral Equations



Pros.

- In 3D space object, apply 2D surface mesh.
- Decrease number of unknowns.
- No truncation needed.
- Well-conditionate matrix.

Cons.

- Impenetrable objects: PEC.
- Piecewise homogenous media.
- Dense (full) matrix.

- Geometrical Modeling Sphere.
- Discretize Surface, i.e., Triangular rooftop function (RWG)
- Electric-Field Integral Equation EFIE for perfect electric conductor PEC Scattering Problems

$$\hat{\boldsymbol{n}} \times \oiint_{S'} \left(\bar{\bar{\boldsymbol{I}}} + \frac{1}{k_0^2} \nabla\nabla \right) G_0(\boldsymbol{r}, \boldsymbol{r}') \cdot \boldsymbol{J}(\boldsymbol{r}')\, dr' = \hat{\boldsymbol{n}} \times \boldsymbol{E}^{inc}(\boldsymbol{r})$$

where

$$G(\boldsymbol{r}, \boldsymbol{r}') = \frac{e^{-jk_0|\boldsymbol{r}-\boldsymbol{r}'|}}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|}$$

- Build on numerical discretization, dense complex matrix equation result.

$$\begin{bmatrix} A_{11} & \cdots & A_{1N} \\ \vdots & \ddots & \vdots \\ A_{N1} & \cdots & A_{NN} \end{bmatrix} \begin{Bmatrix} x_1 \\ \vdots \\ x_n \end{Bmatrix} = \begin{Bmatrix} b_1 \\ \vdots \\ b_n \end{Bmatrix}$$

N is the number of unknows, for electrically very large objects, N can increase to the order of billions.

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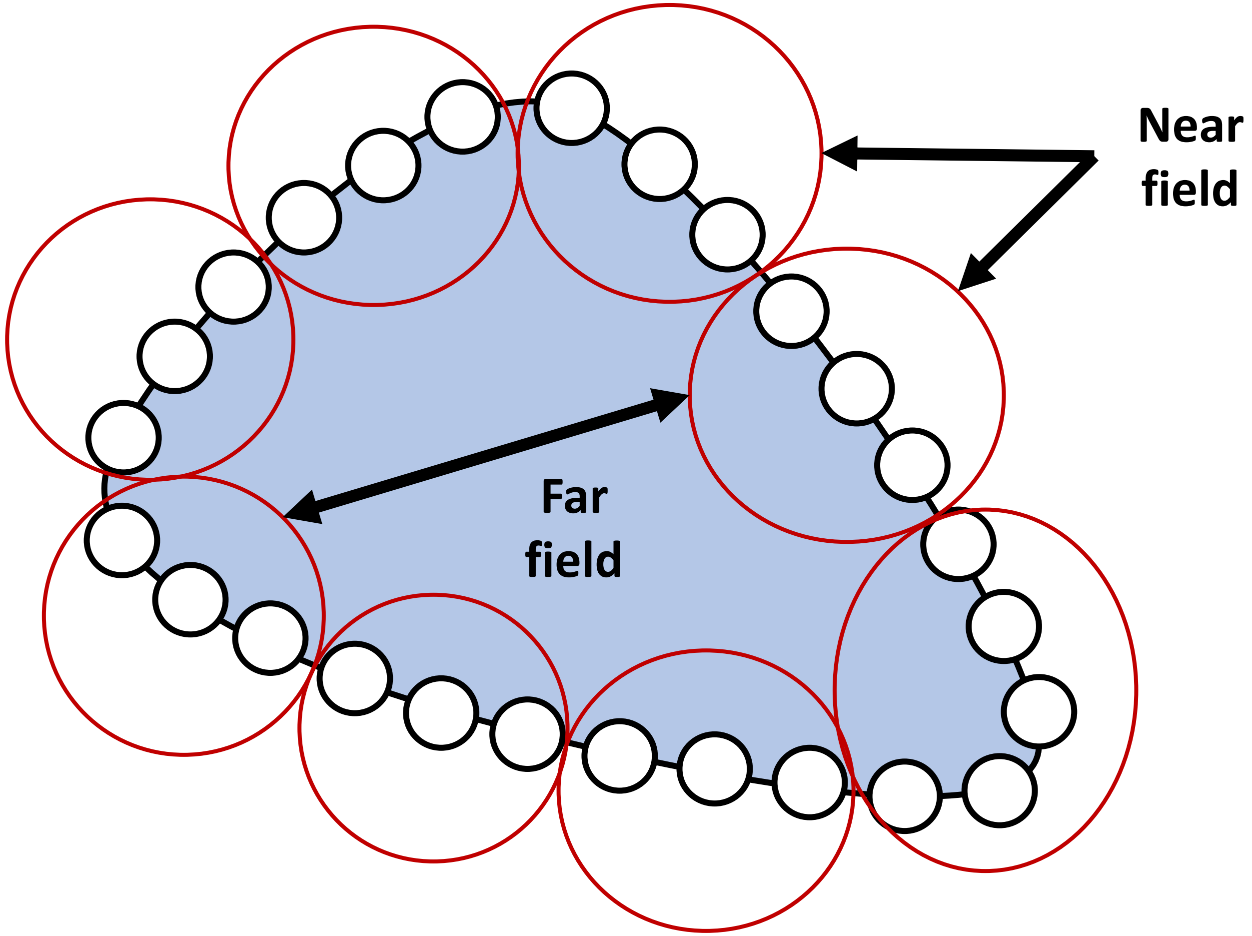
Fast Algorithms

- Fast Multiple Method (FMM)
  - Matrix product in MoM equivalent to self & mutual interaction in field radiated by elements
  - Group the elements by their location (near).
  - Reduce scattering centers.



Multilevel Fast Multipole Algorithm (MLFMA)

- Extended MoM-based FMM.
- Subdivides boundary element mesh into clusters.
- Reduce all calculations to the midpoints of clusters.
- Almost no loss of accuracy.
- Multiple level Clustering.

Algorithm Complexities

Method	Complexity		
	Storage	Time	
		Iterative Solver	Direct Solver
MoM	$O(N^2)$	$O(N^2)$	$O(N^3)$
FMM	$O(N^{1.5})$	$O(N^{1.5})$	
MLFMA	$O(NlogN)$	$O(NlogN)$	

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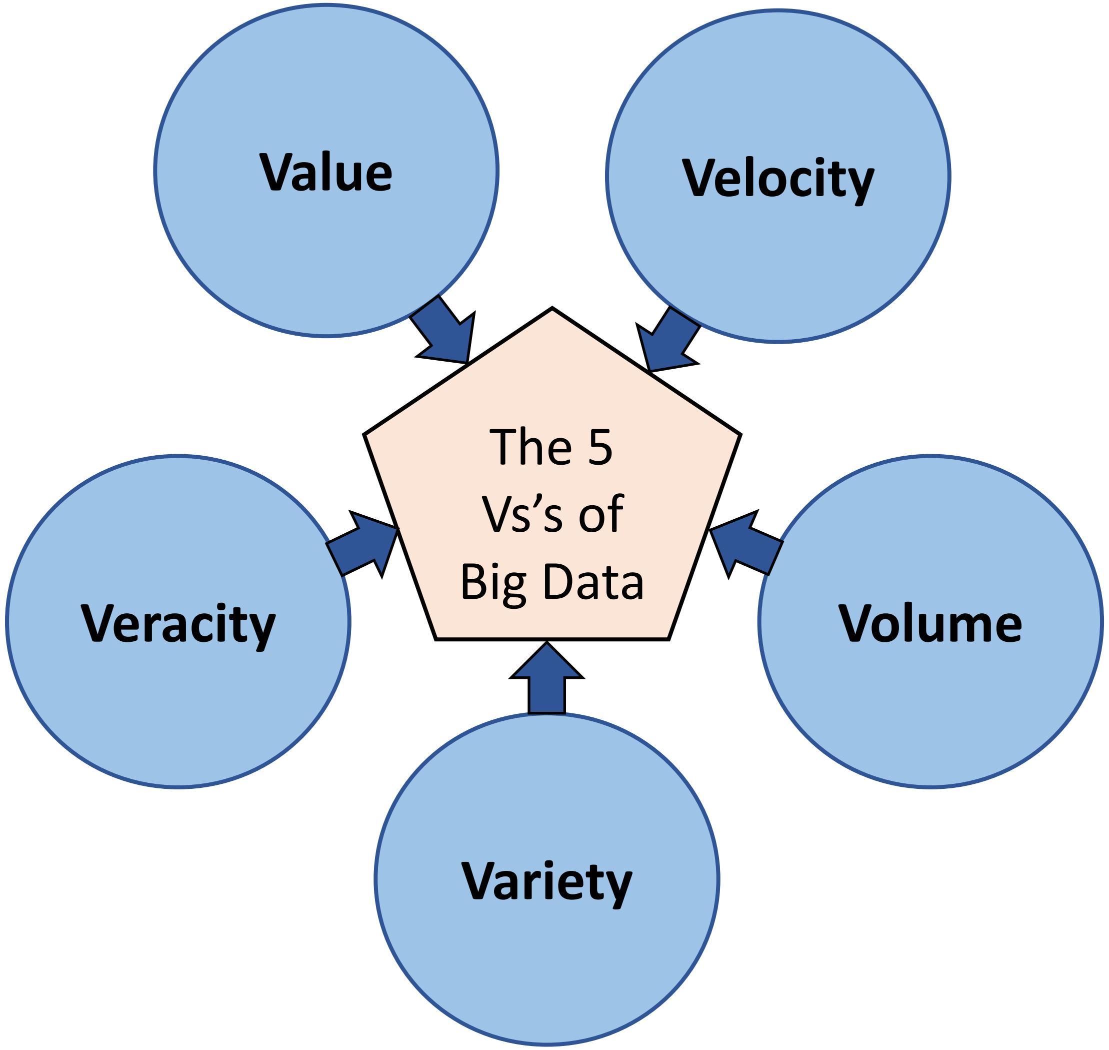
Big Data

- **Volume**: exponential increase in data resulting from new technologies; large size.
- **Velocity:** rate of growth and how fast data is gathered for analysis.
- **Value:** indicative of substantial value, including the ability to understand your target better, target them accordingly, and optimize performance.
- **Variety:** information about the various types of data, such as structured, unstructured, semi-structured, etc.
- **Veracity:** means the confidence established about the data to be used.



Big Data Techniques in Electromagnetic Engineering Problems

- Electromagnetic Spectrum has shown four big data characteristic.[1]
  - Variety, Volume, Value, and Velocity.
- Data Mining.
  - For abnormal Spectrum detection in real-time. [1]
- Symbolic Regression.
  - To derive a full-wave analytical expression for the characteristic impedance of microstrip (fits large data set).[2]

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Continue

- Machine Learning.
  - Reinforcement learning for antenna design and optimization.[3]
  - Deep learning for microwave filter circuit design.[4]
- Gas and Oil Industry.
  - Markov Chain Monte Carlo (MCMC) for Large-Scale Georsteering inversion using directional electromagnetic logging measurements.[5]
- High Performance Computing.
  - Convergence between Big Data Analytics and HPC.[6]
  - Parallel Computing in CEM.
- Prediction Techniques.
  - Predict number and location of scattering grating lobes by an antenna array.[7]

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Thank you