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Connecting Minds. Exchanging Ideas.

SAN DIEGO2023

TU1A-4

# AI and Machine Learning for Microwaves

## A Highlight of

# Past, Present and Future Trends

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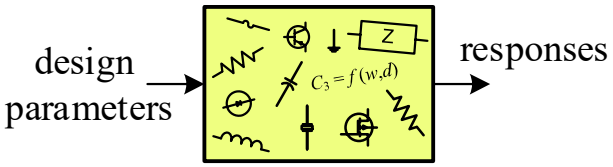
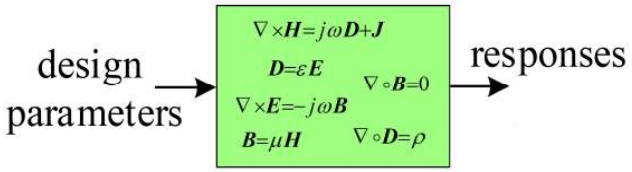
Carleton University, Ottawa, Canada

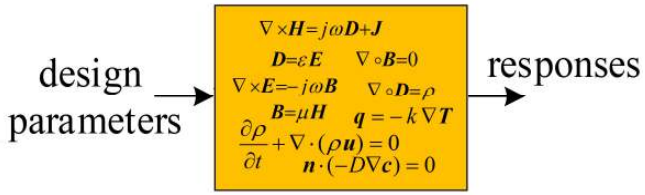
# Component Modeling/Simulation



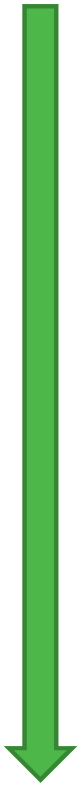

**Equivalent circuit**




**EM**




**Multiphysics**



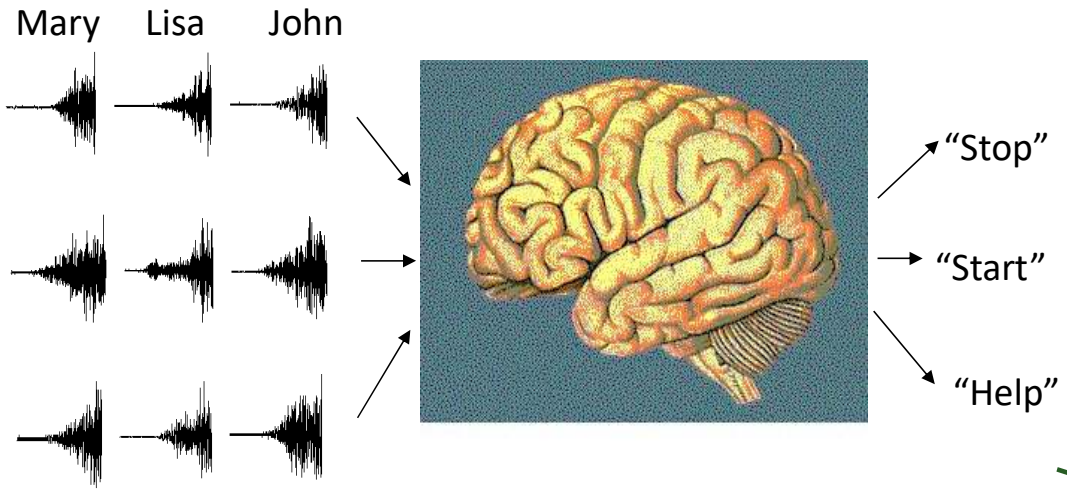
More accurate solutions

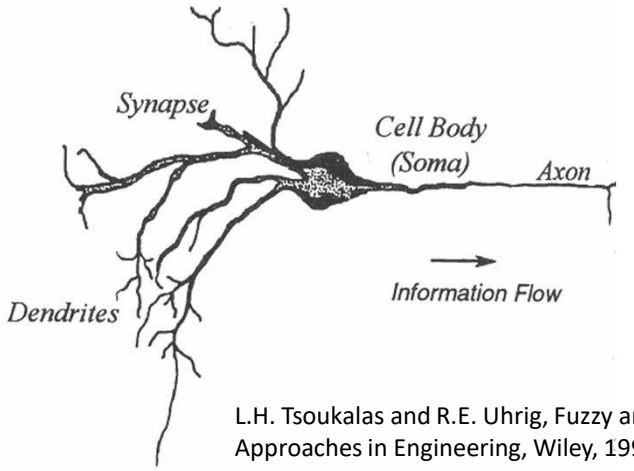
More computationally intensive

More equations
More variables
More complex algorithms

# From Biological Learning to Machine Learning

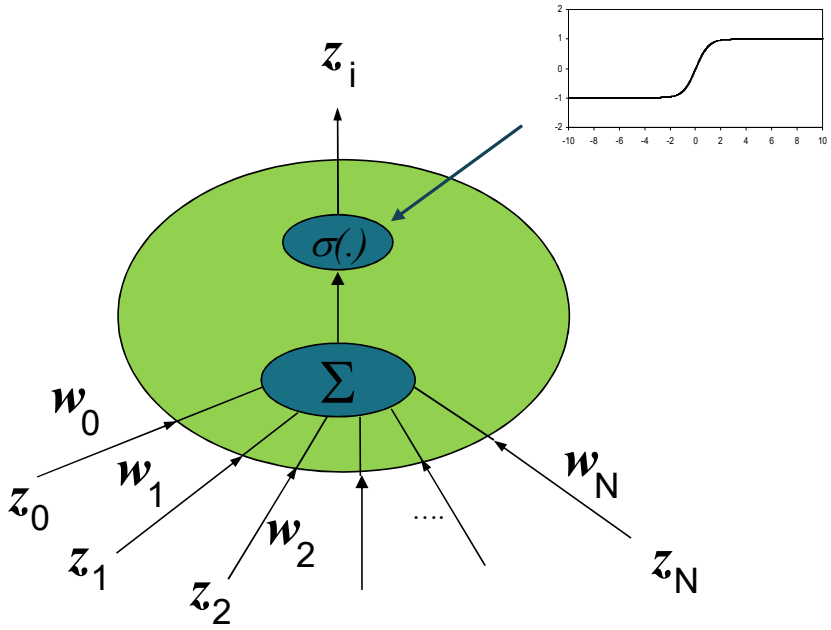
## - Biological Neural Network



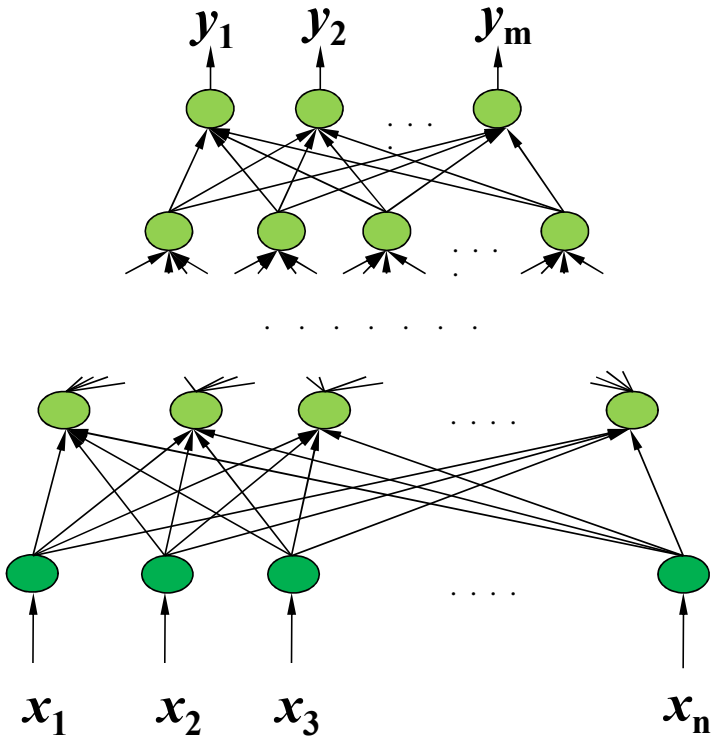




L.H. Tsoukalas and R.E. Uhrig, Fuzzy and Neural Approaches in Engineering, Wiley, 1997

# Artificial Neural Network (ANN)




Artificial neuron




Artificial neural network

# Universal Approximation Theorem

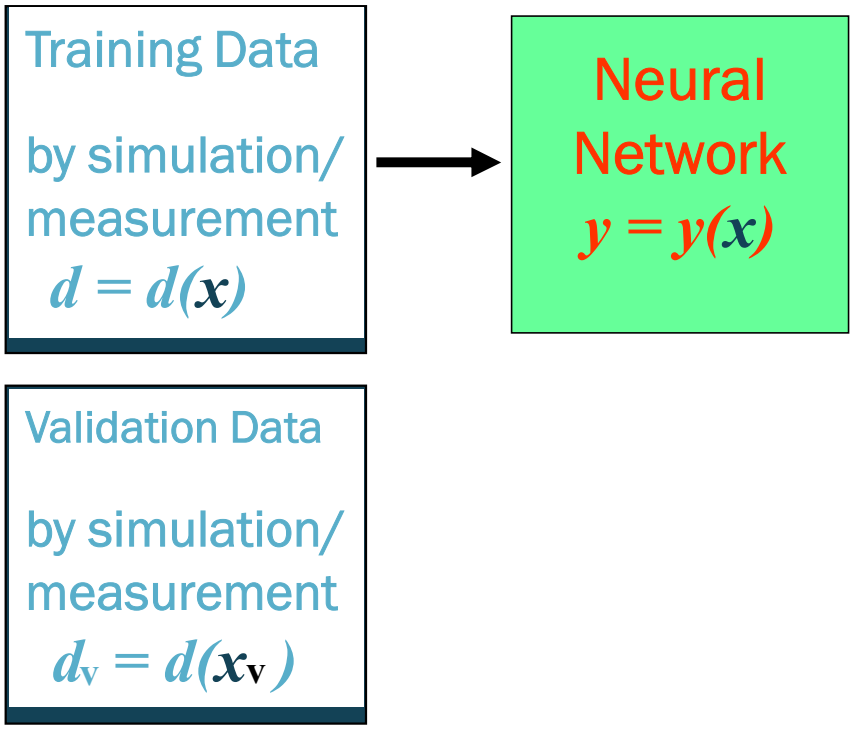
Mathematical theorem published by Cybenko in 1989

Summary in plain words:

Given enough hidden neurons, a multilayer perceptron with at least 1 hidden layer can approximate an arbitrary continuous multidimensional function to any required accuracy.

# Neural Network Training






Objective:

to adjust $w$ such that

$$\min_{w} \sum_{x} (y - d)^2$$

# Early Works of ANN for Microwave Design

- **Microwave impedance matching** (Vai, Prasad, IEEE MGL 1993)
- **Microstrip circuit design** (Horng, Wang, Alexopoulos, IMS 1993)
- **Analysis and optimization of microwave circuits** (Zaabab, Zhang, Nakhla, IMS 1994)
- **Modeling via interconnects in microstrip circuits** (Watson, Gupta IMS 1996)
- **Microwave CAD** (Creech, Paul, Lesniak, Jenkins, Lee, Calcatera, IMS 1996)

- **Microwave optimization and statistical design** (Zaabab, Zhang, Nakhla, T-MTT, 1995)
- **Microwave circuit analysis and design** (Vai, Prasad, T-MTT 1995)
- **Modeling vias and interconnects in dataset circuits** (Watson, Gupta, T-MTT 1996)

# Historical Events of ANN for Microwaves in IMS

- 1st Workshop:

  **Workshop on Applications of ANN to Microwave Design**
  IEEE MTT-S IMS (Denver, Colorado), 1997.
  Chairs: K.C. Gupta and M.S. Nakhla;
  Speakers: L. Mahajan, K.C. Gupta, M.S. Nakhla, G.L. Creech, Q.J. Zhang

- 1st Short Course:

  **Applications of ANN to RF and Microwave Design**
  *IEEE MTT IMS,* (Boston, Massachusetts), June 2000.
  Instructors: K.C. Gupta and Q.J. Zhang

# Applications of ANN to RF and Microwave Design

*(Special Issue of the Int. J. RF Microwave CAE, 1999)*

- **Review of ANN, and filter modeling and classification** (Burrascano, Fiori and Mongiardo)
- **Synthesis of transmission line structures** (Watson, Cho and Gupta)
- **Microwave circuit design beyond black box models** (Vai and Prasad)
- **Large-signal device modeling and nonlinear circuit design** (Harkouss, Rousset, et. al.)
- **RBF models for MESFET and HEMT intermodulation distortion** (Garcia et. al.)
- **ANN structures and training** (Wang and Zhang)
- **Use of prior knowledge for ANN development** (Watson, Gupta and Mahajan)
- **Neurocomputing in IC process applications** (Creech and Zurada)
- **ANN for filter design trained with FEM EM data** (Fedi, Gaggelli, Manetti and Pelosi)
- **Wavelet neural net for EM based optimization** (Bila, Harkouss, Ibrahim, Rousset et. al.)
- **Calculation of the bandwidth of microstrip antennas** (Sagiroglu, Guney and Erler)

# Examples of Research Directions in ANN for Microwave Design

- General applications of ANN to microwave design
- Knowledge-based neural networks
- Neural networks for parameterized modeling of EM structures
- Neural network based models for microwave transistors
- Neural network based behavioral modeling of nonlinear circuits
- Inverse modeling
- Neural network structure and training algorithms

# Machine Learning in Microwave Engineering

*Special Issue of the IEEE Microwave Magazine, Oct. 2021*

*Guest Editors: Costas Sarris, Q.J. Zhang*

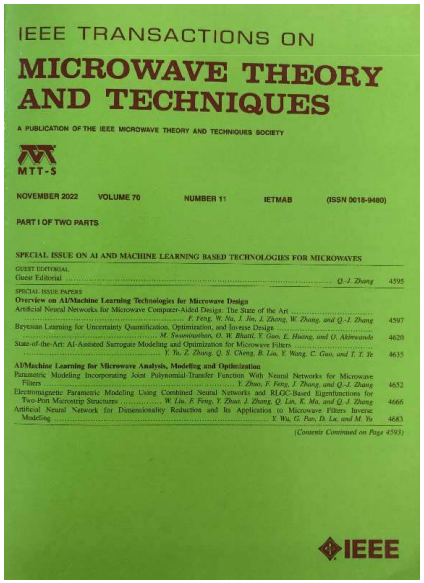
- Machine Learning in Microwave Engineering (Sarris, Zhang)
- Design Space and Frequency Extrapolation: Using Neural Networks (Bhatti, Nikita, Swaminathan)
- ANNs for Fast Parameterized EM Modeling: (Feng, Na, Jin, W. Zhang, Q. Zhang)
- Enabling Automatic Model Generation of RF Components: A Practical Application of Neural Networks (L. Zhang, Kabir, Sweeney, Kim)

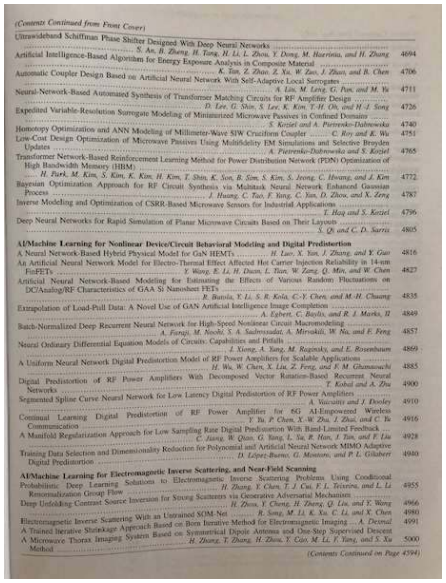
# AI/ML Based Technologies for Microwaves

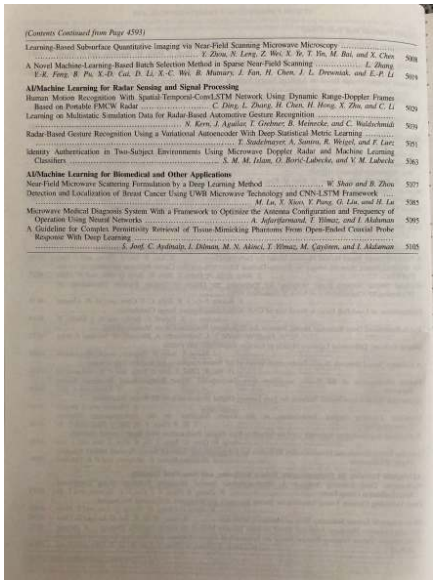
*Special Issue of the IEEE Trans. MTT (Nov. 2022)*
*Guest Editor: Q.J. Zhang*

209 full-paper submissions

45 accepted/published


IEEE TRANSACTIONS ON
MICROWAVE THEORY AND TECHNIQUES
A PUBLICATION OF THE IEEE MICROWAVE THEORY AND TECHNIQUES SOCIETY
NOVEMBER 2022 VOLUME 70 NUMBER 11 IETMAB (ISSN 0018-9480)
PART I OF TWO PARTS
SPECIAL ISSUE ON AI AND MACHINE LEARNING BASED TECHNOLOGIES FOR MICROWAVES





# AI/ML Based Technologies for Microwaves

*Special Issue of the IEEE Trans. MTT (Nov. 2022)*
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## Overviews of AI/Machine learning

ANN for microwave computer-aided design (Feng et al);

Bayesian learning for uncertainty quantification, optimization and inverse modelling (Swaminathan, et al)

AI-assisted surrogate modelling and optimization of microwave filters (Yu, et al)

# AI/ML Based Technologies for Microwaves

*Special Issue of the IEEE Trans. MTT (Nov. 2022)*

AI/ML approaches for analysis, forward/inverse modelling and optimizations for microwave design

AI/ML technologies for nonlinear device modelling, power amplifier (PA) behavioural modelling and digital predistortion,

AI/ML for electromagnetic inverse scattering, near-field scanning, or electromagnetic imaging

AI/ML for radar sensing and signal processing

AI/ML for biomedical and other applications

# AI/ML Based Technologies for Microwaves

*Special Issue of the IEEE Trans. MTT (Nov. 2022)*

## Machine Learning Methodologies

ANNs
deep learning
convolutional neural networks (CNN)
recurrent neural networks (RNN)
long-short term memory networks (LSTM)
generative-adversarial networks (GAN)

k-means clustering
support vector machine (SVM)
Gaussian process (GP) regression
Bayesian optimization (BO),
reinforcement learning (RL),
U-net etc;

# AI/ML Based Technologies for Microwaves

*Special Issue of the IEEE Trans. MTT (Nov. 2022)*

**Microwave Applications**

| | |
|---|---|
| modelling and design: passives - | planar and 3D electromagnetic structures |
| | microwave filters |
| | SIW circuits |
| | high-speed IC packages |
| modelling and design: actives - | GaN-HEMT/FinFET/nanosheet FET |
| | PA/DPD, MIMO transmitters |

**Electromagnetic imaging for breast cancer detection/localization, thorax imaging**

**Doppler radar based human motion recognition, gesture recognition and object identification**

# AI/ML Day in IMS2023

*Organizers: Q.J. Zhang and Costas Sarris*

- AI/ML Bootcamp (Q.J. Zhang, C. Sarris, U. Gustavsson) Bootcamp on Sunday
- AI/ML for RF PA Design and Digital Predistortion (A. Zhu, R. Ma) Workshop WMC
- Brain-Inspired Learning for Intelligent Spectrum Sensing (L. Katehi), Invited talk
- AI/ML Technologies for Microwaves (Q.J. Zhang, C. Sarris), Special Session Tu1A
- AI/ML Technologies for Signal and Power Integrity (J.E. Rayas-Sanchez, C. Sarris), Focus Session Tu3A
- AI/ML based Wireless System Design and Operation – Hope or Hype ? (C. Sarris, Q.J. Zhang, O. Eliezer, B. Sadhu) Panel Session PL2
- Machine Learning for RF to mm-Wave Systems (A. Tang and Q.J. Zhang), Technical Session Tu2A

# AI and Machine Learning for Microwaves

Machine learning (such as neural networks) exploited in microwave area since 1990s.

Activity in machine learning intensified in recent years

Ongoing Activities and Trends

new algorithms, ML structures, microwave knowledge-based ML methods

component level - EM, GaN HEMTs, ..

circuit/system level - PA, DPD, MIMO, intelligent wireless systems

application level - biomedical, security, autonomous systems, communications

new and emerging applications

# Thank You