

TU1A-4

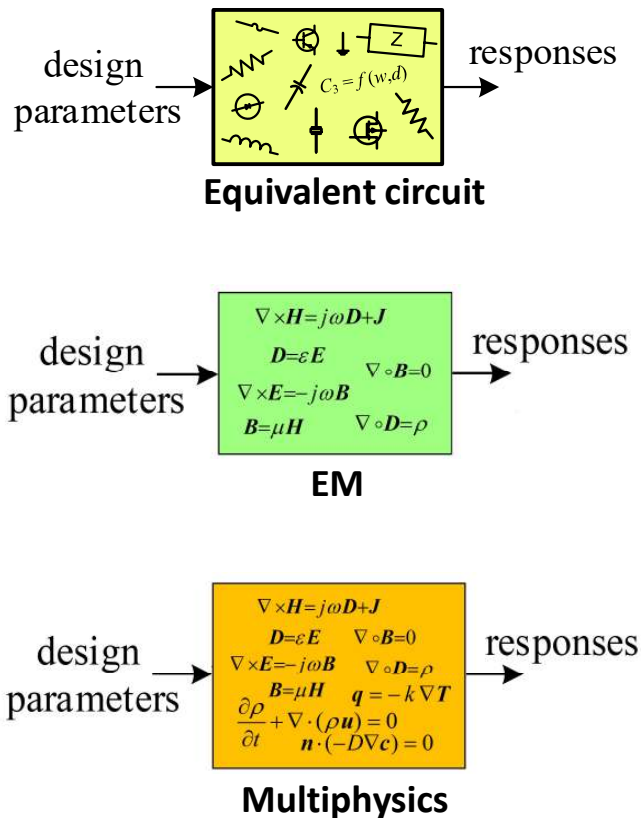
# AI and Machine Learning for Microwaves

## A Highlight of Past, Present and Future Trends

Q.J. Zhang

Carleton University, Ottawa, Canada

# Component Modeling/Simulation



More accurate solutions

More computationally intensive

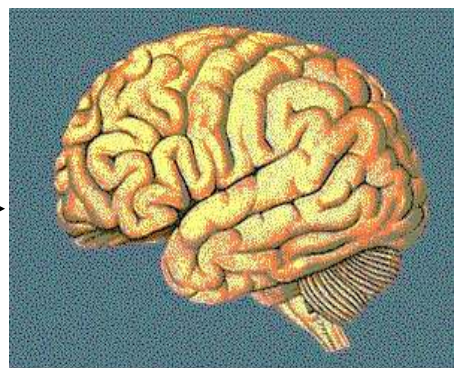
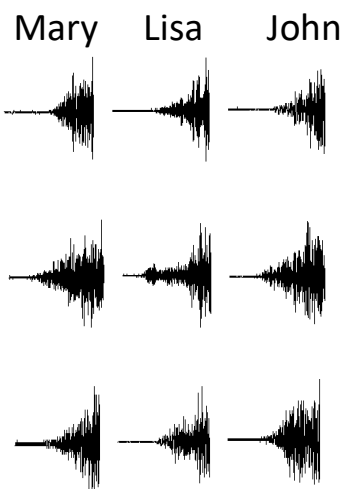
More equations

More variables

More complex algorithms

# From Biological Learning to Machine Learning

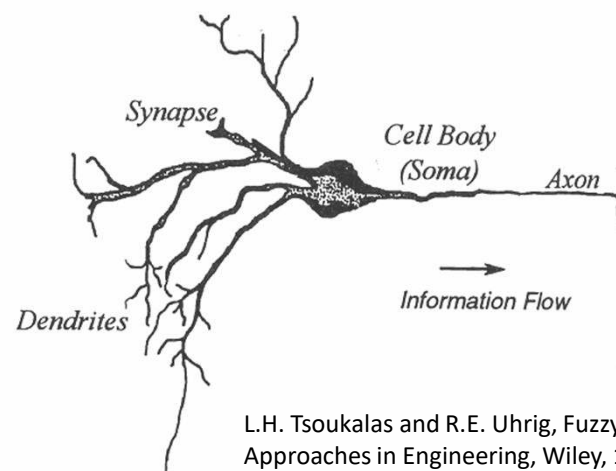
## - Biological Neural Network



"Stop"

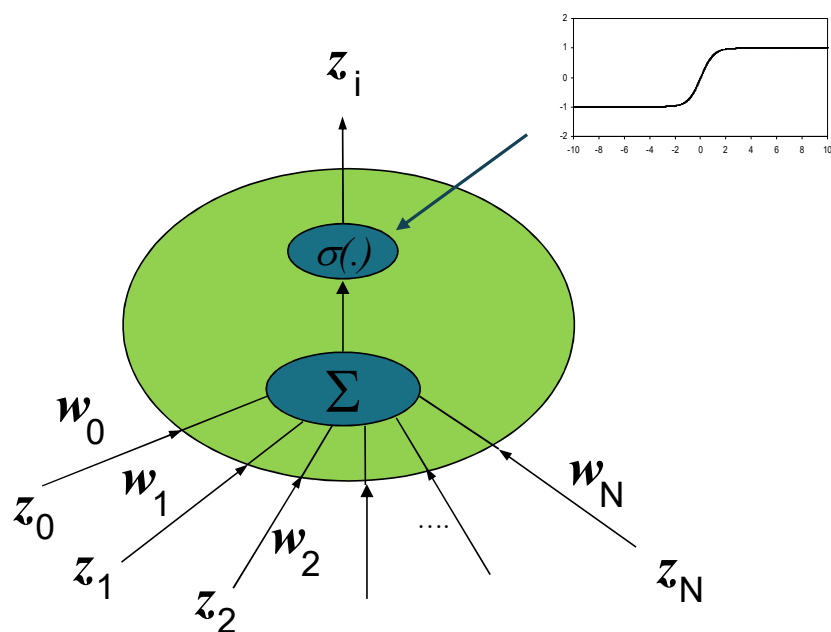
"Start"

"Help"

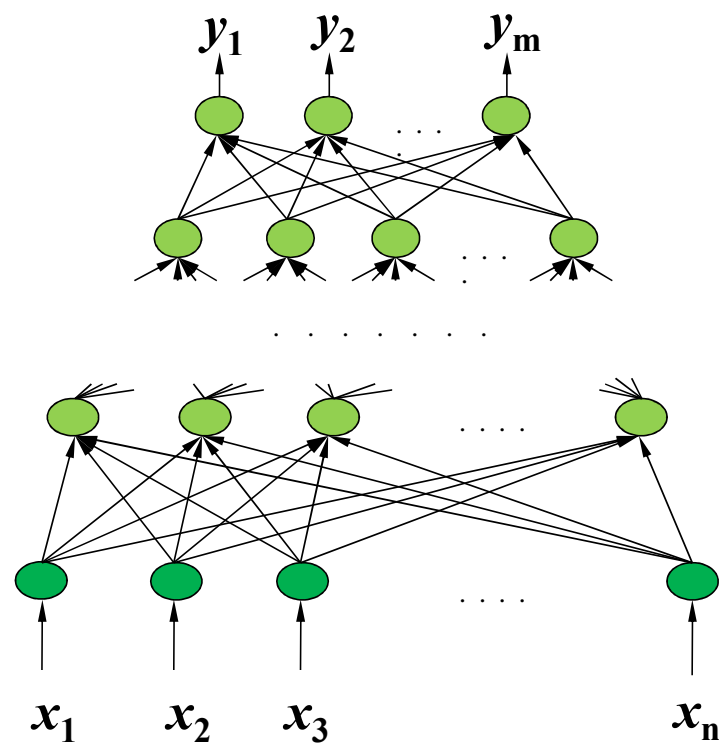


L.H. Tsoukalas and R.E. Uhrig, Fuzzy and Neural Approaches in Engineering, Wiley, 1997

# Artificial Neural Network (ANN)



Artificial neuron



Artificial neural network

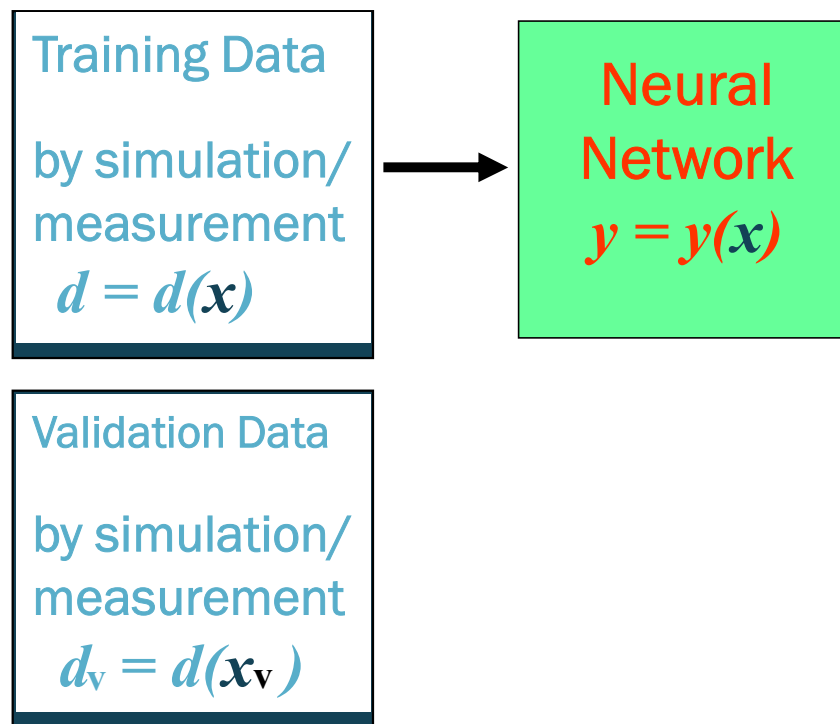
# Universal Approximation Theorem

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

$$\underset{w}{\text{minimize}} \sum_x (y - d)^2$$

# 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, Calcaterra, 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

- 1<sup>st</sup> 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
- 1<sup>st</sup> 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

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# AI/ML Based Technologies for Microwaves

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

*Guest Editor: Q.J. Zhang*

## 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