Artificial Intelligence and Machine Learning for RF and Microwave Design:

practical technologies for present and future applications

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KEYSIGHT TECHNOLOGIES

Outline

- Introduction to AI, ML and ANN
- ANN for electronic device modeling
- ANN for electronic behavioral modeling
- Summary

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- **Introduction to AI, ML and ANN**
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AI and ML

AI

ML

Supervised Learning

Regression

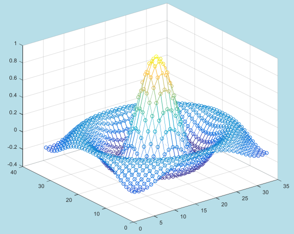
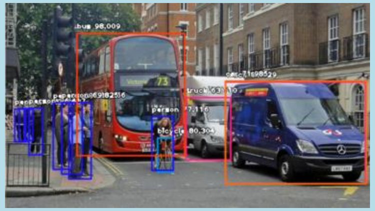
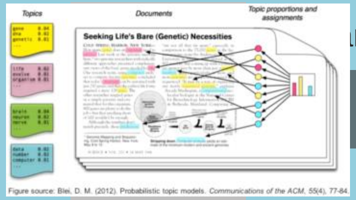


Image classification

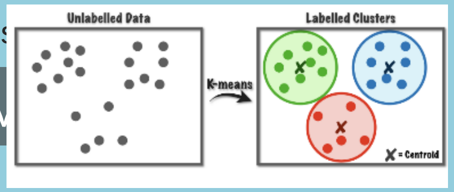


Face recognition
Speech to text
Text translation

Unsupervised Learning



Topic Modeling



Clustering

Reinforcement Learning

Video games

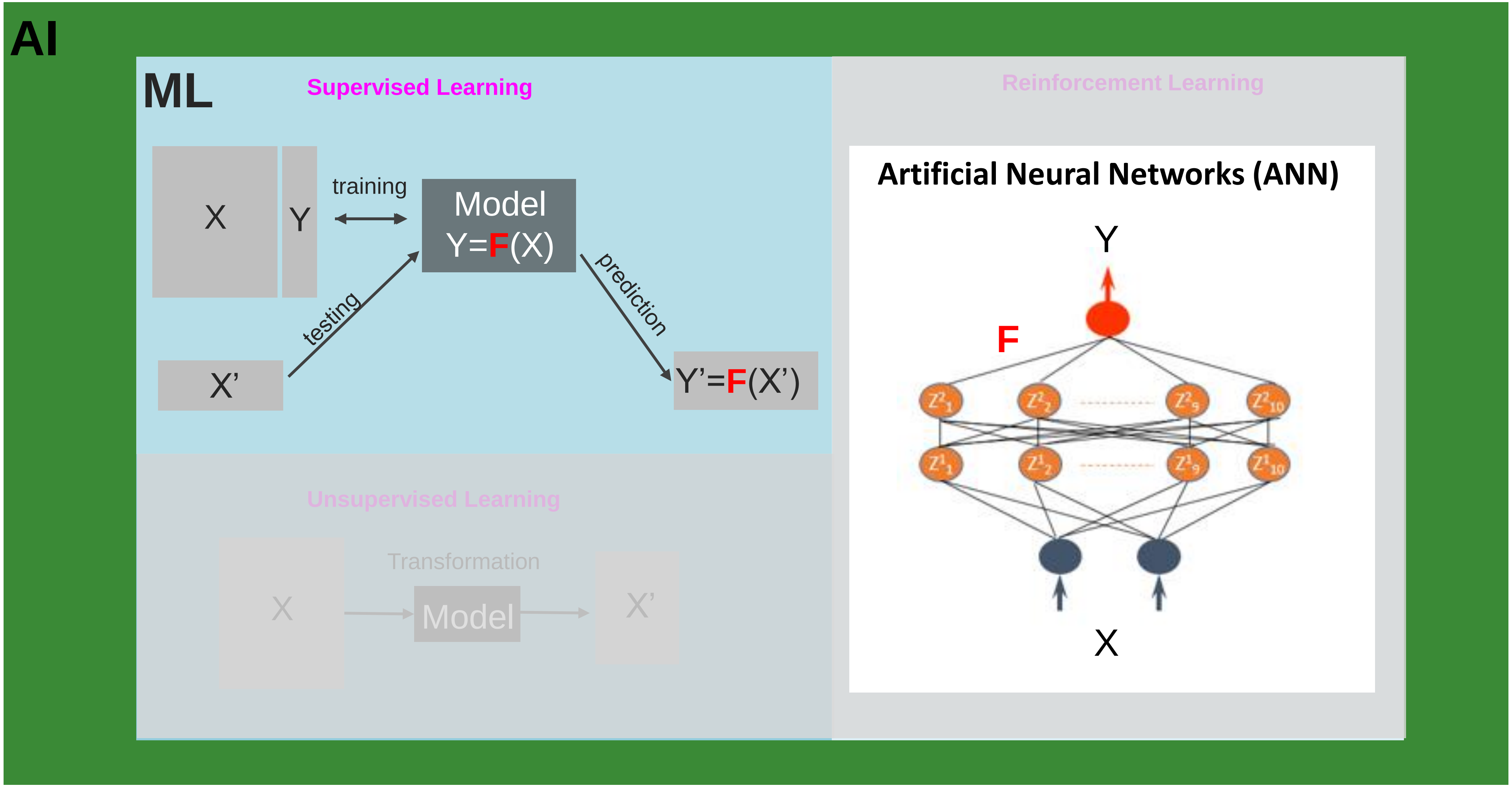
Alpha Go

Stock trading

Walking, jumping, etc.

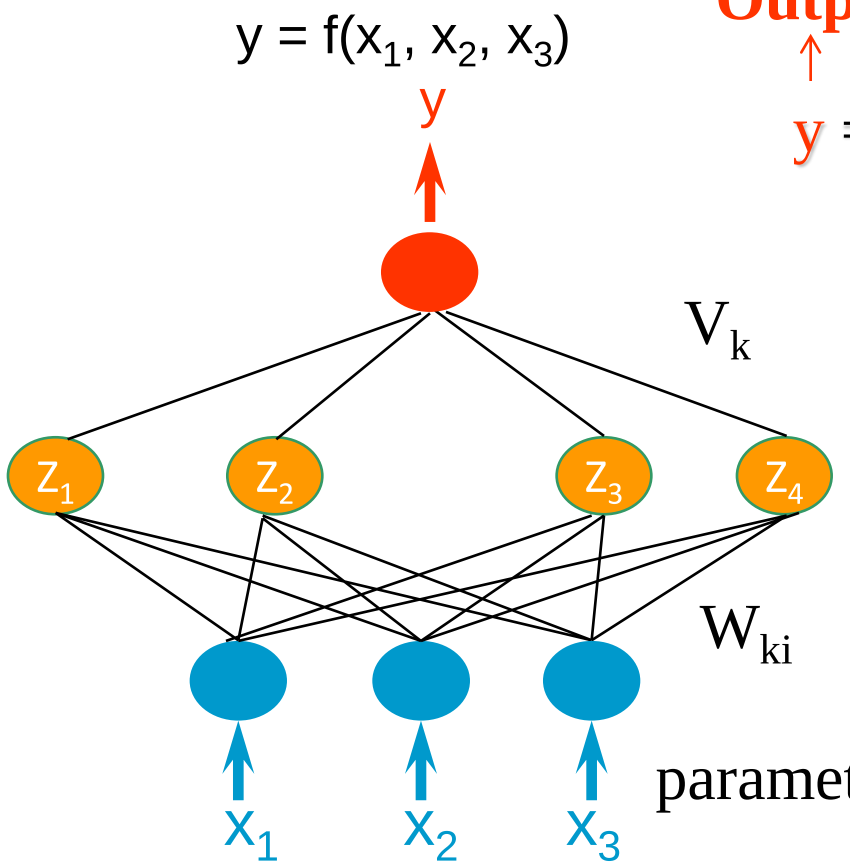
Self-driving cars

AI and ML



KEYSIGHT TECHNOLOGIES

Introduction to Artificial Neural Networks (ANN)

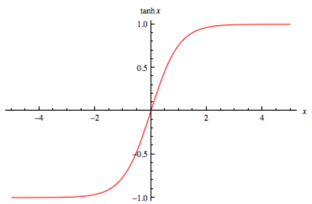


Outputs

$$y = \sum_k V_k Z_k$$

Hidden Neuron Output

$$Z_k = \tanh\left(\sum W_{ki} x_i \right)$$



Inputs

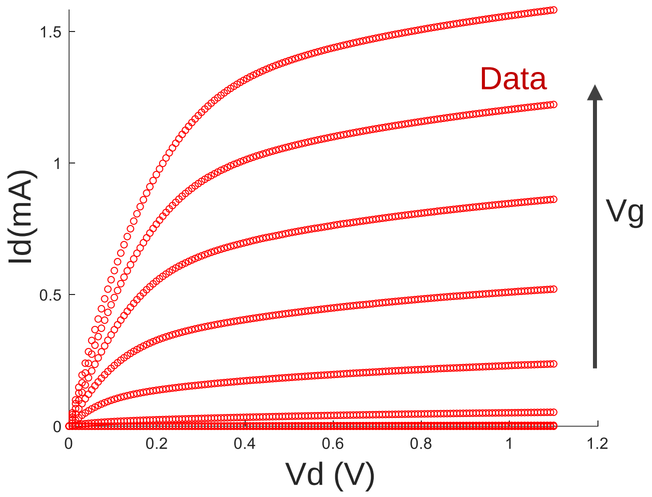
parameters $\boldsymbol{w} = [W_{ki}, V_k]$

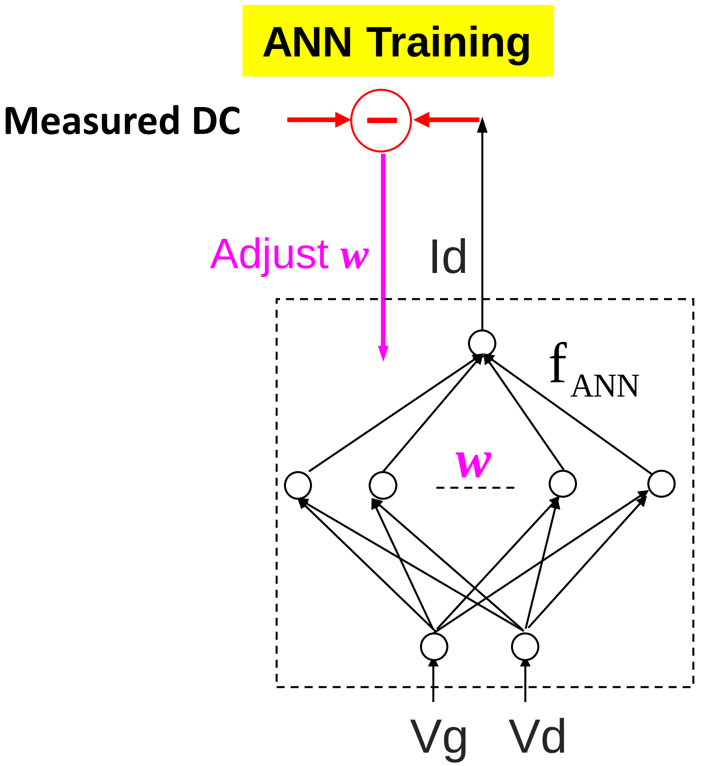
Universal approximation Theorem:

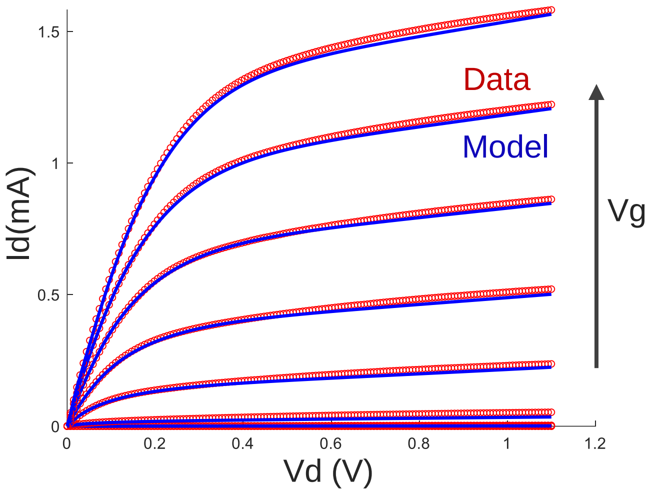
Can fit any nonlinear function of many variables

- Easy to train *on scattered data*
- Fast to evaluate
- Infinitely differentiable
- Simple link (Verilog-A, ONNX, …) to Simulators

Introduction to Artificial Neural Networks (ANN)







Well-known training methods (e.g. back-propagation)

- No equation development needed
- No user-defined parameter extraction strategy

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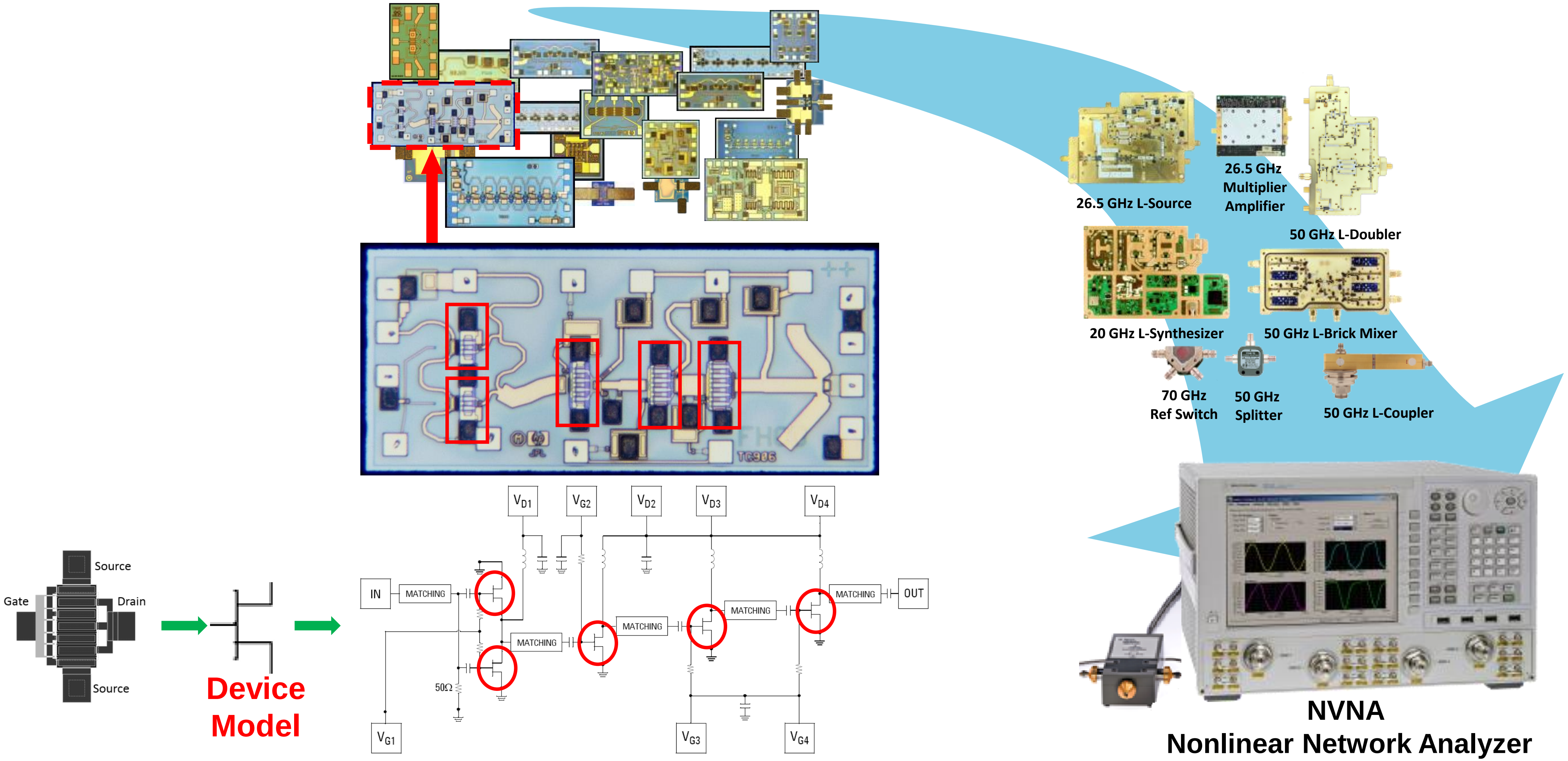
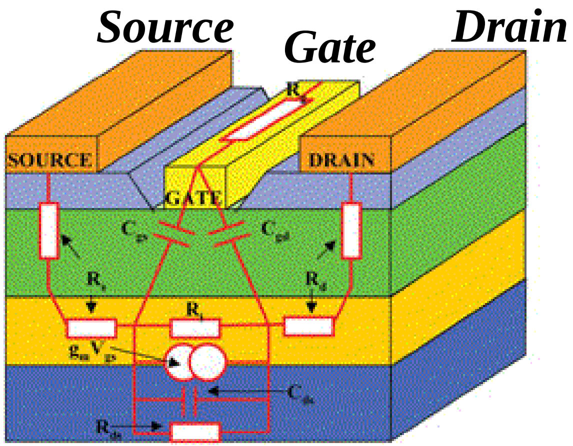
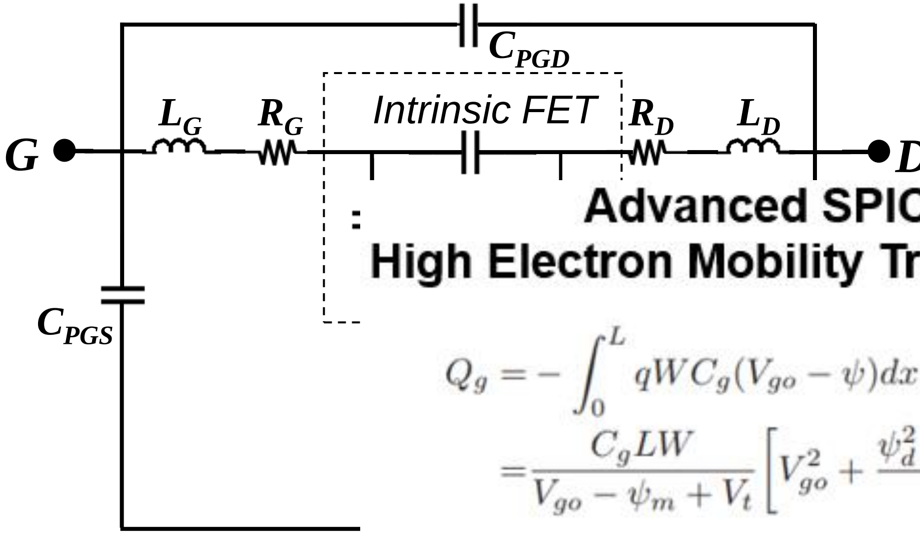
Device Modeling



KEYSIGHT TECHNOLOGIES

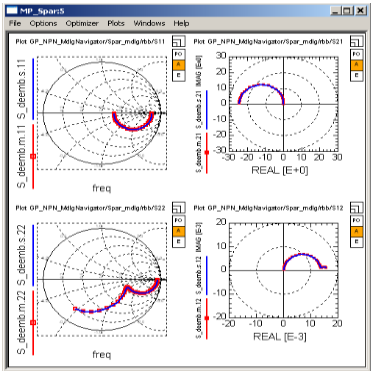
Conventional Device Modeling Flow



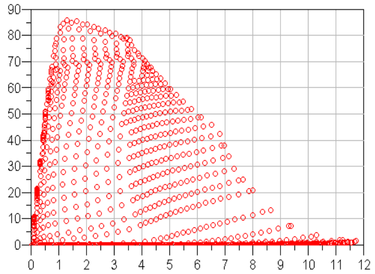


Advanced SPICE Model for High Electron Mobility Transistor (ASM-HEMT)

VNA



DC



Q_{GS}

ANN Training

I_{DS}

$$Q_g = -\int_0^L qWC_g(V_{go}-\psi)dx$$

$$= \frac{C_g LW}{V_{go}-\psi_m+V_t}\left[V_{go}^2 + \frac{\psi_d^2+\psi_s^2+\psi_d\psi_s}{3} - V_{go}(\psi_d+\psi_s-V_t) - V_t\psi_m\right]$$

$$I_{ds} = \frac{\mu_{eff}C_g}{\sqrt{1+\theta_{sat}^2\psi_{ds}^2}}\frac{W}{L}(V_{go}-\psi_m+V_{th})(\psi_{ds})(1+\lambda V_{ds,eff})$$

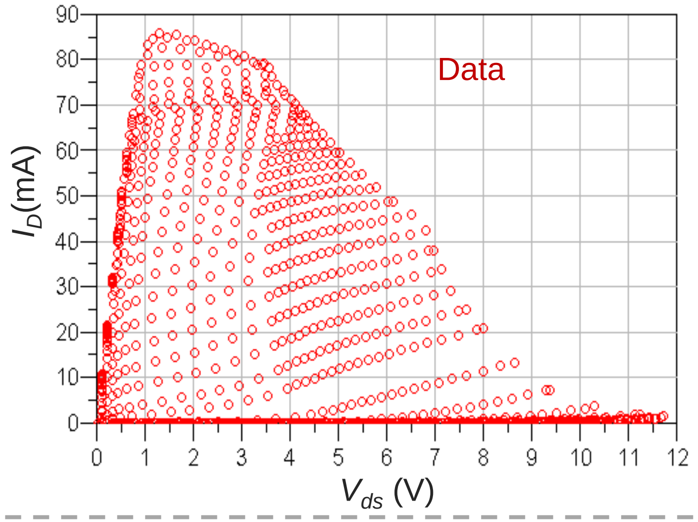
$$E_{f,unified} = V_{go} - \frac{2V_t ln\left(1+e^{\frac{V_{go}}{2V_t}}\right)}{\frac{1}{H(V_{go,p})}+(C_g/qD)e^{-\frac{V_{go}}{2V_t}}}$$

$$H = \frac{V_{go}+V_t\left[1-ln(\beta V_{gon})\right]-\frac{\gamma_0}{3}\left(\frac{C_gV_{go}}{q}\right)^{\frac{2}{3}}}{V_{go}\left(1+\frac{V_t}{V_{god}}\right)+\frac{2\gamma_0}{3}\left(\frac{C_gV_{go}}{q}\right)^{\frac{2}{3}}}$$

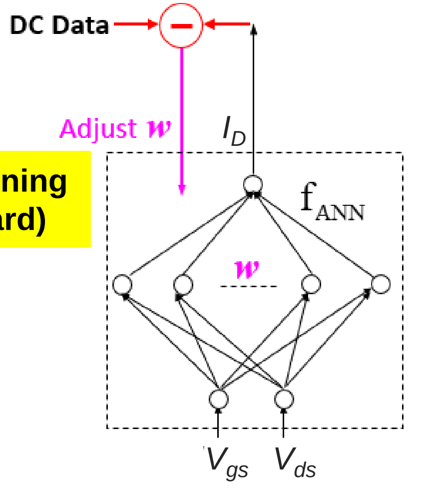
KEYSIGHT TECHNOLOGIES

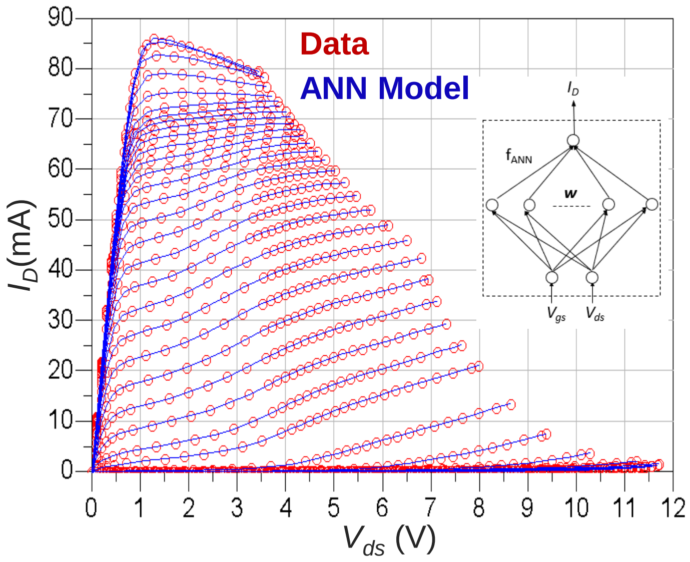
ANN Training

I_D

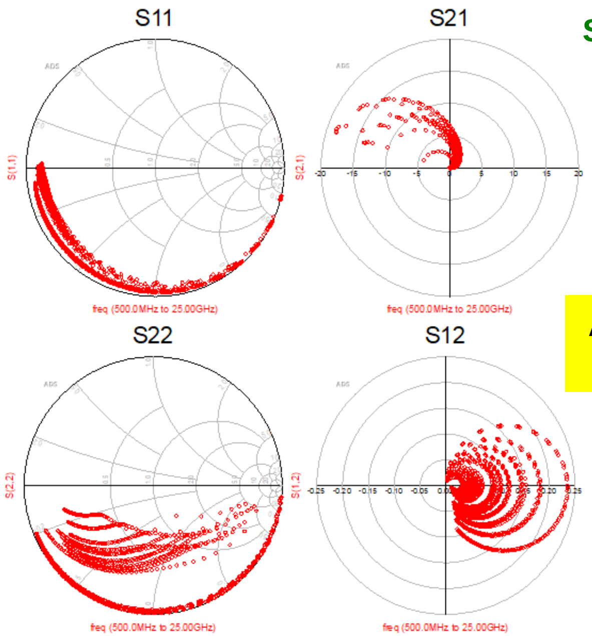


ANN Training (Standard)





Q_G

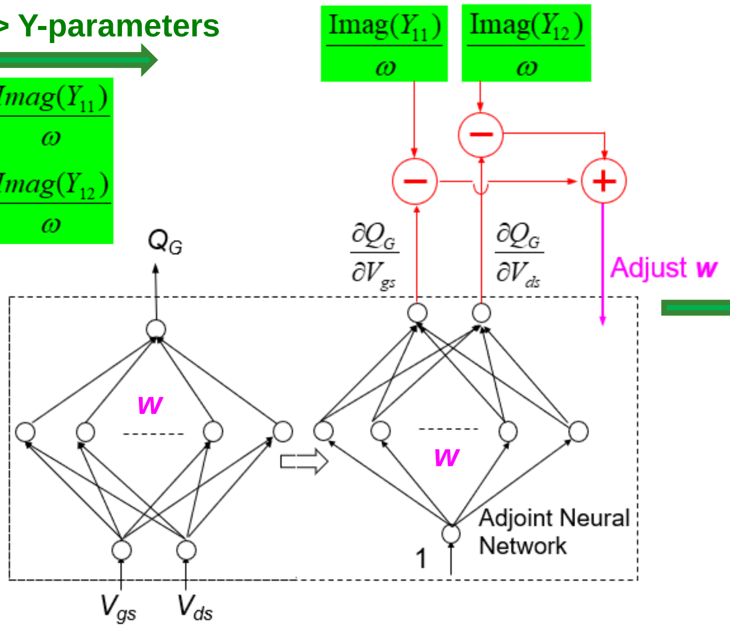


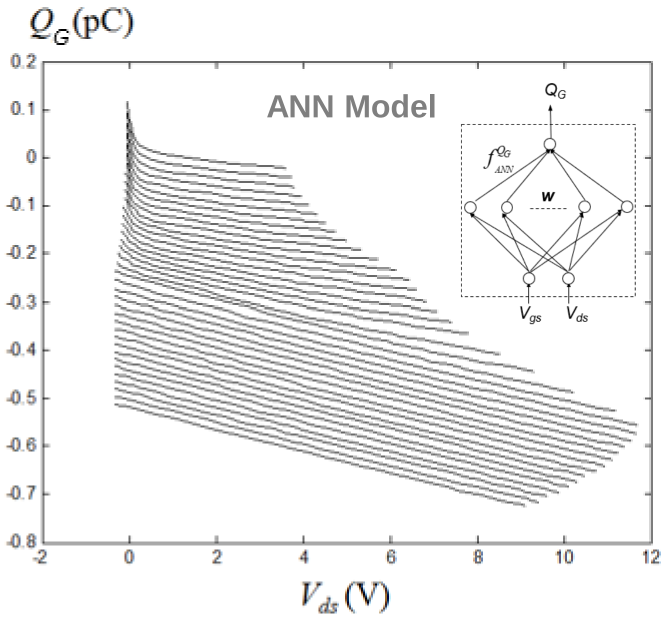
S-parameters -> Y-parameters

$$\frac{\partial Q_G}{\partial V_{gs}} = \frac{Imag(Y_{11})}{\omega}$$

$$\frac{\partial Q_G}{\partial V_{ds}} = \frac{Imag(Y_{12})}{\omega}$$

ANN Training (Adjoint [1])

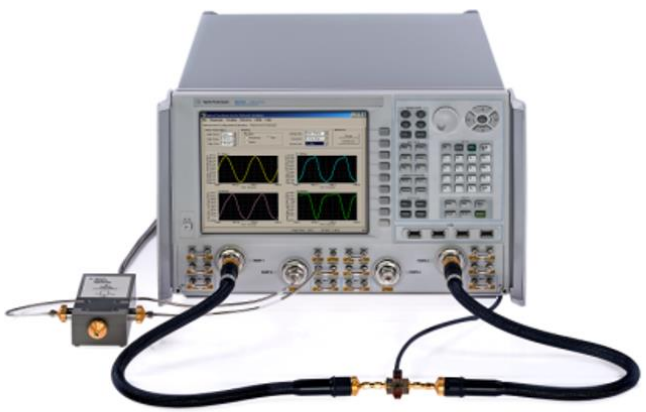


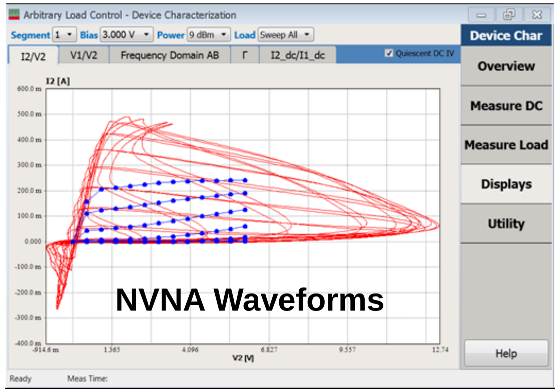


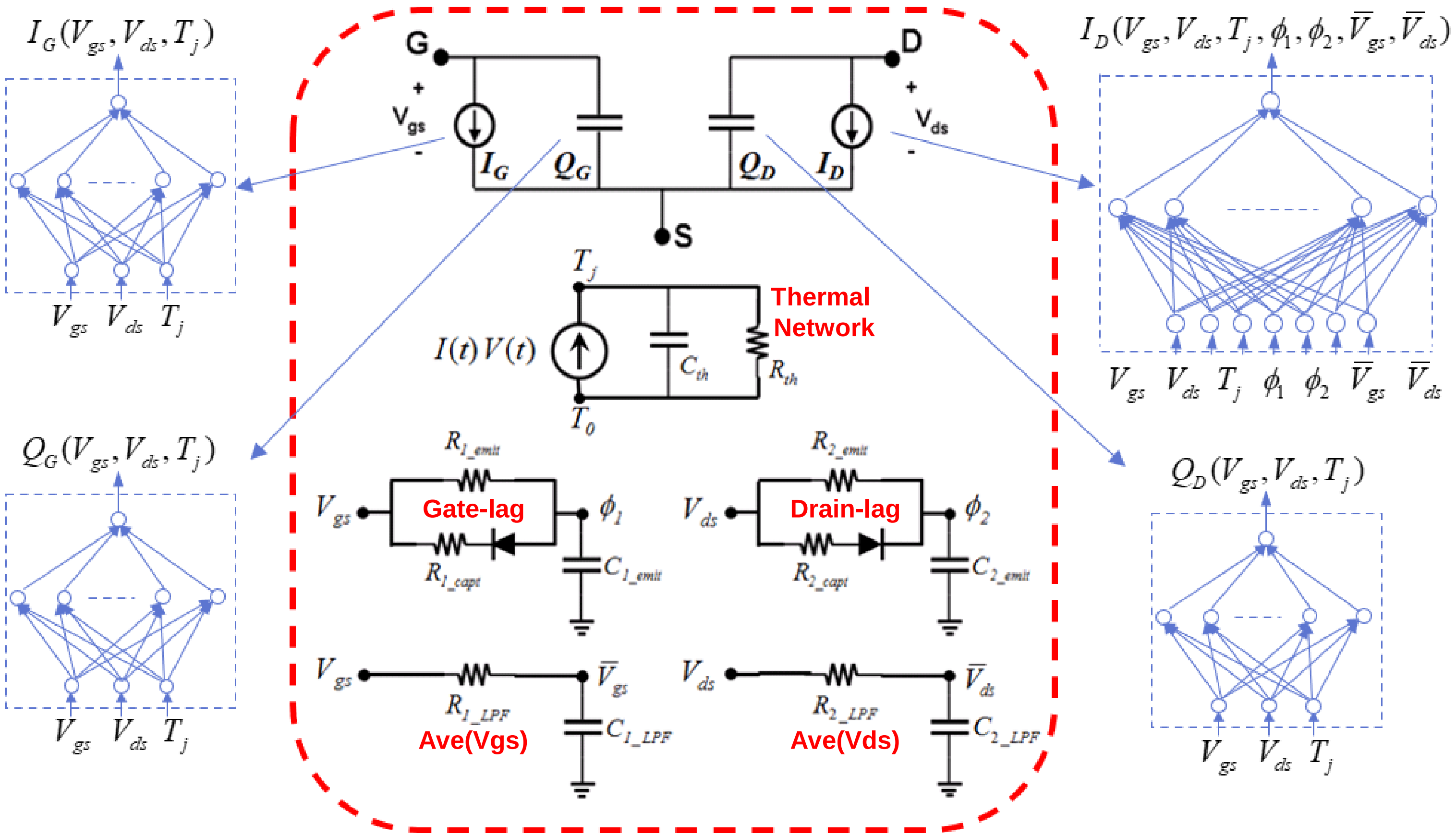
KEYSIGHT TECHNOLOGIES

[1] J. Xu et al, "Exact adjoint sensitivity analysis for neural based microwave modeling and design," *IEEE Trans. Microw. Theory Tech*, vol. 51, pp.226-237, 2003.

ANNs in DynaFET [2] model for GaN transistors







- **Richer data necessary to identify complicated dynamics**

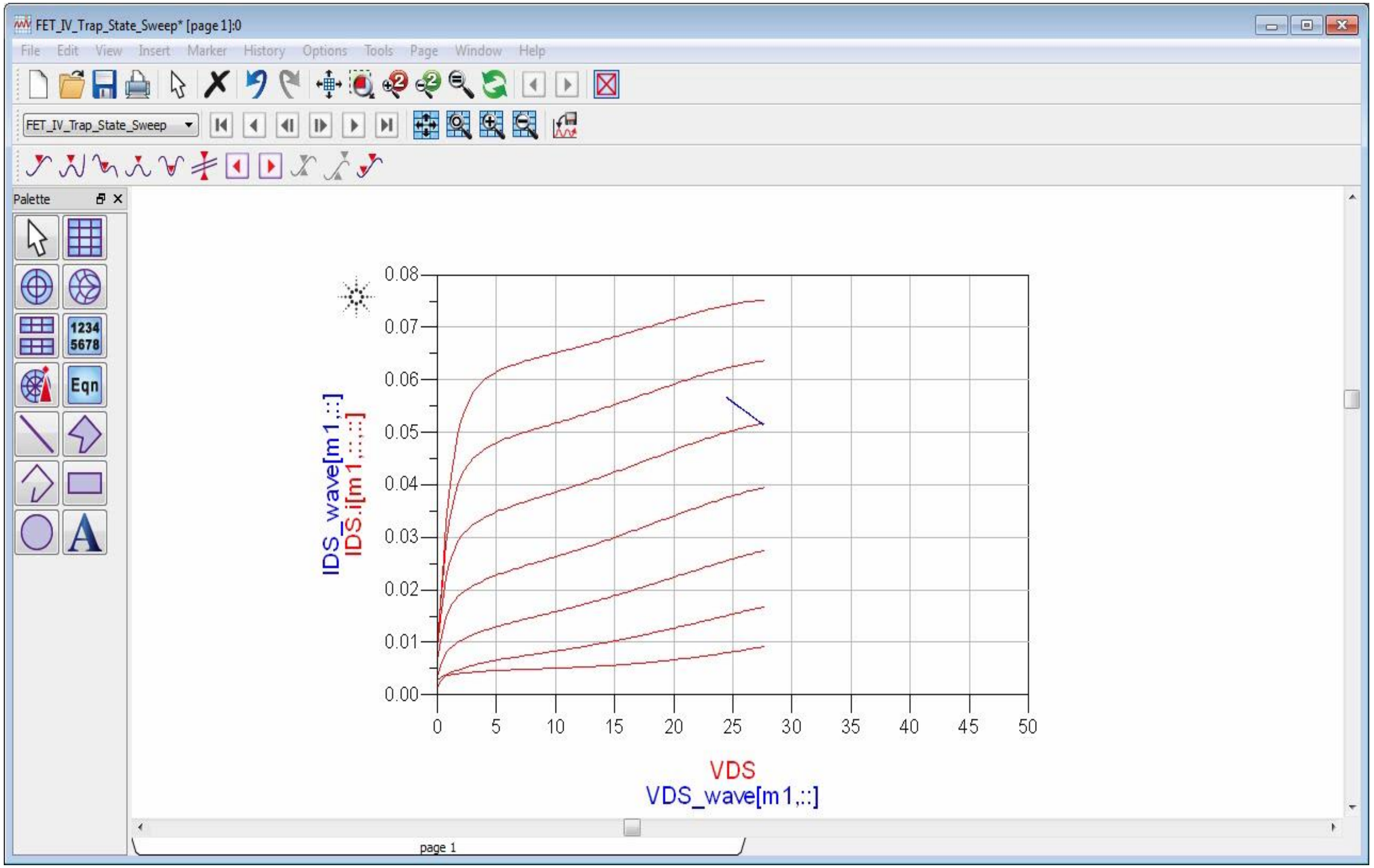
- **ANNs used to model the detailed, general, multi-variate coupling**
  - Accurate and general
  - No additional assumptions (e.g., backgating/virtual gate)

- ***One global model* that predicts, simultaneously:**
  - DC and S-parameters
  - Large-signal nonlinearities(distortion,load-pull,PAE)
  - Long-term memory effects
  - No application-specific model tuning needed

KEYSIGHT TECHNOLOGIES

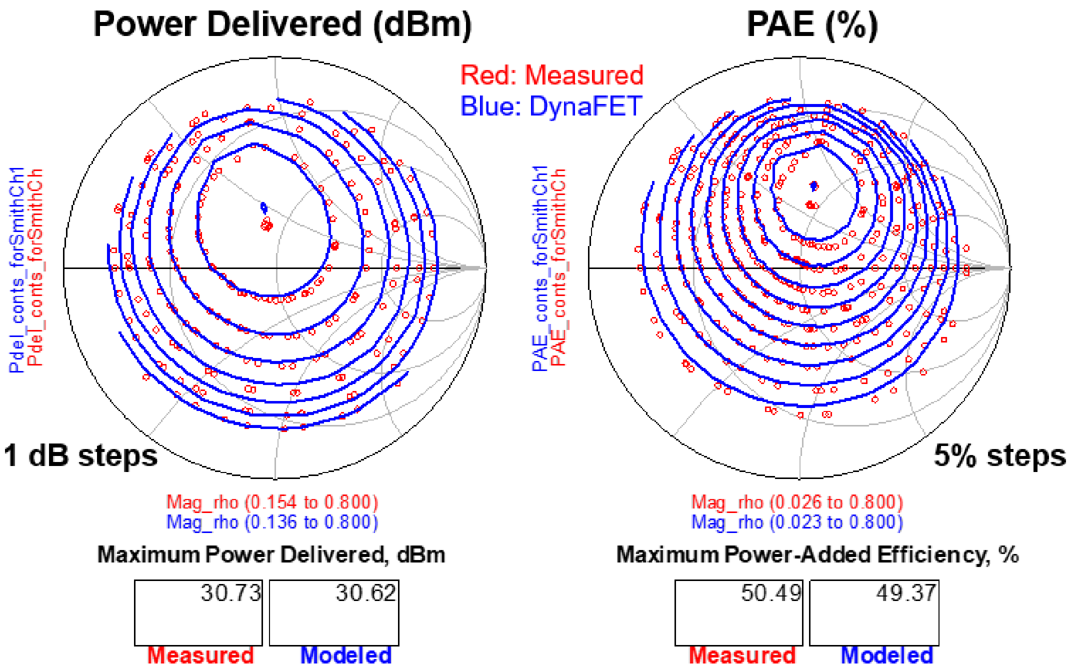
[2] J. Xu et al, “Dynamic FET Model - DynaFET - for GaN Transistors from NVNA Active Source Injection Measurements,” *IEEE MTT-S Int. Micro. Symp. Dig.*, June 2014.

DynaFET model for GaN transistors [2]



Raytheon 6x60μm GaN HFET

Model Validations – Load-pull Contours
fund=10GHz, @Vd=12V, Id=54mA, Pin=24dBm



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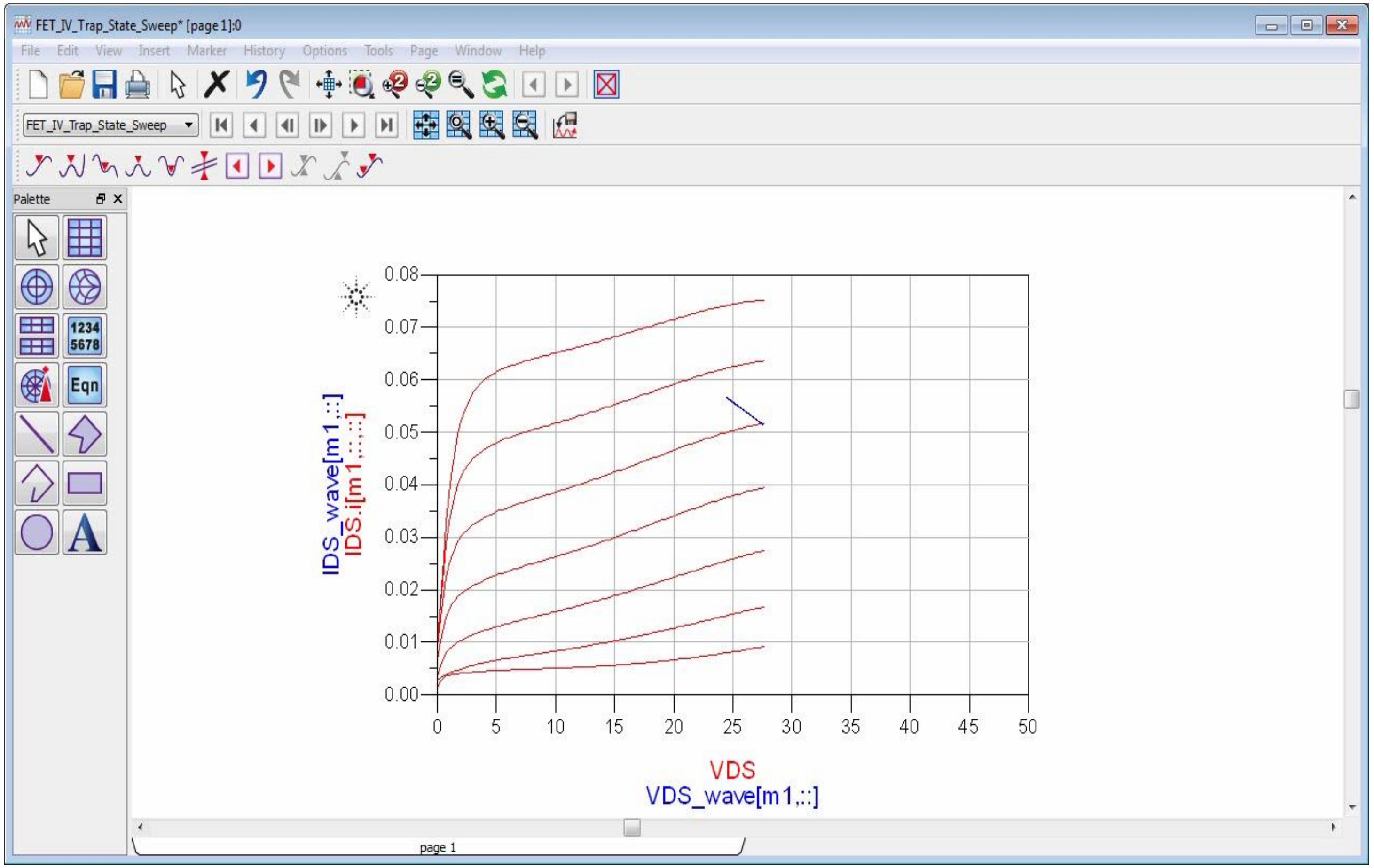

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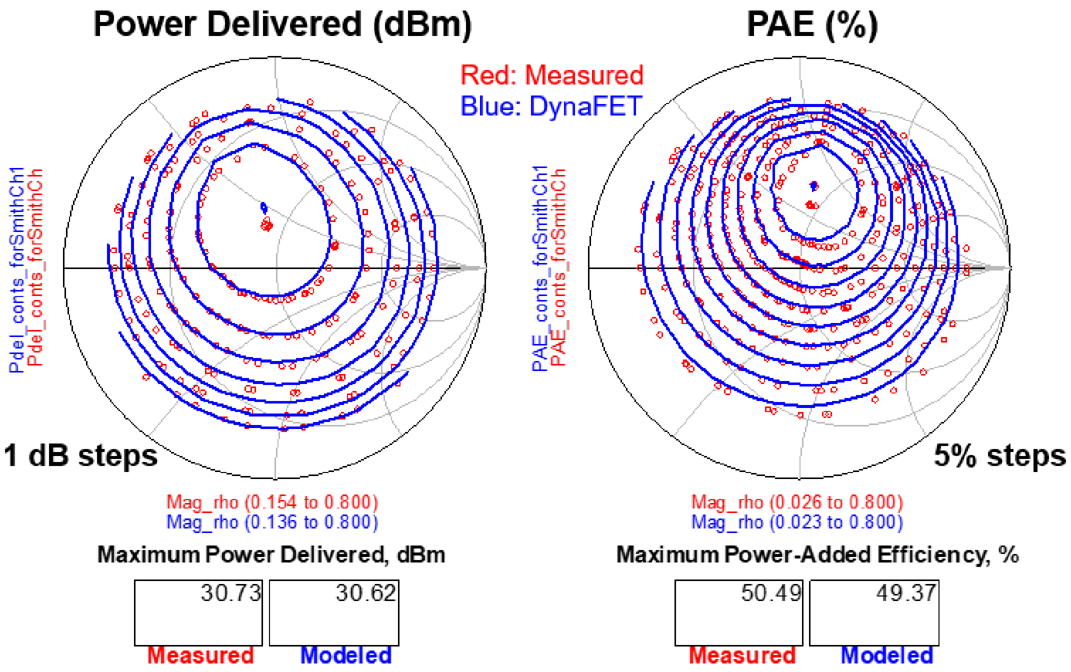

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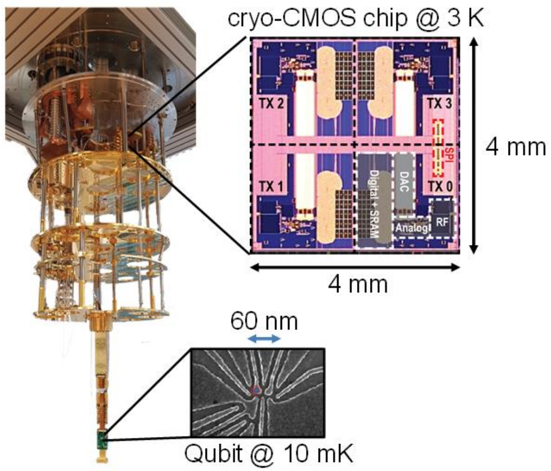
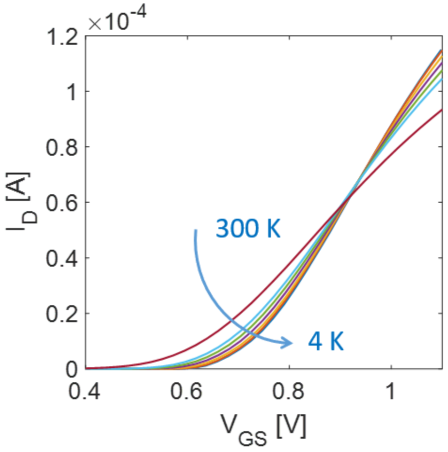
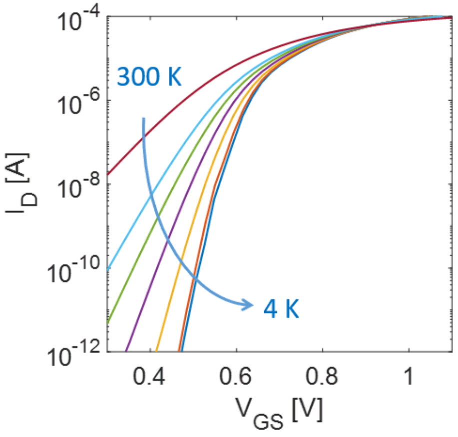
ANN for Cryogenic CMOS Modeling [3]

Enabling circuit simulations for quantum control applications



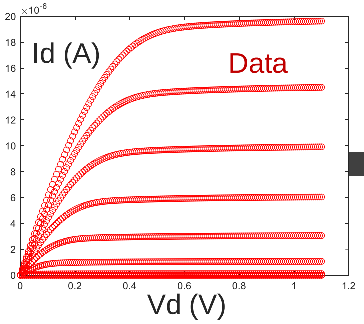


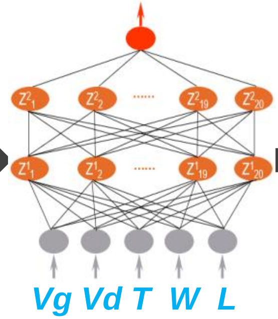


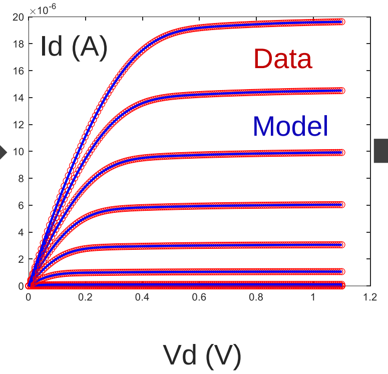
- **Device characteristics at cryogenic temperatures are different from those at room temperature**
- **Existing models and extraction procedures may not be effective**
- **So far, there is not yet consensus on a standard cryo-CMOS model**

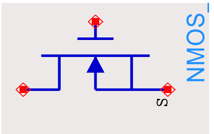
Cryo Work Flow

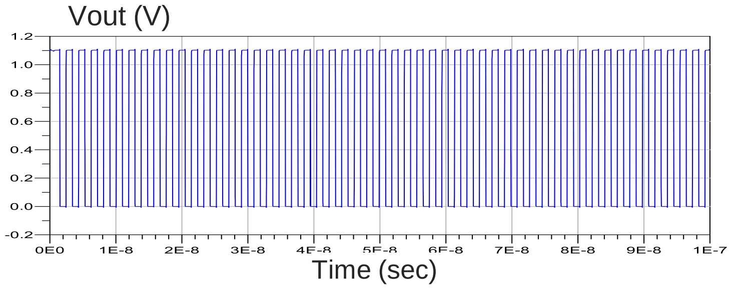
$$I_d = I_d^{ANN}(Vg, Vd, T, W, L)$$



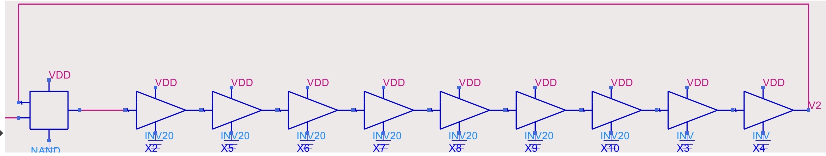








data → **ANN training** → **Accurate Model Linked to ADS** →



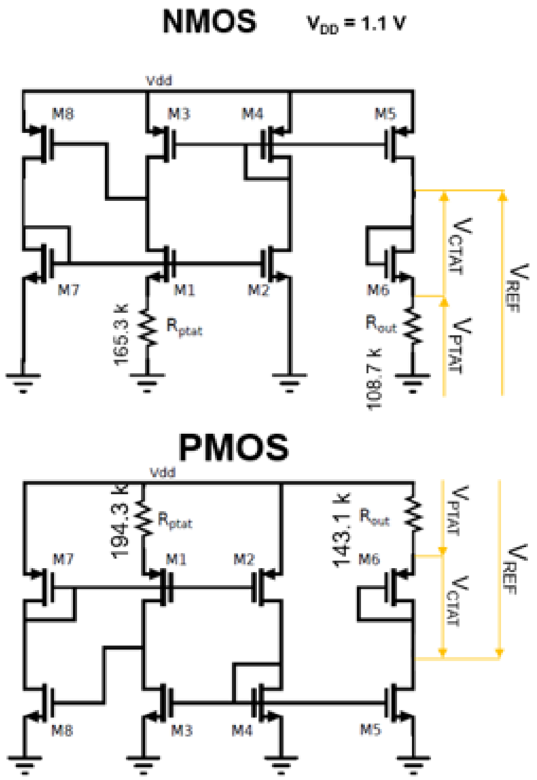
Design and Simulate Cryogenic Circuits

KEYSIGHT TECHNOLOGIES

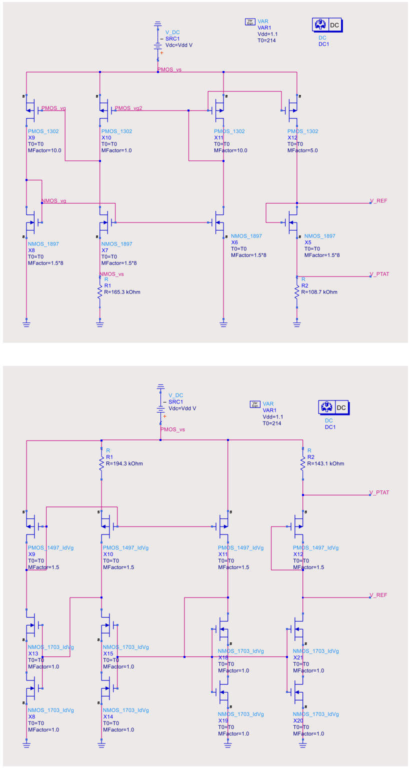
[3] P.A. ‘t Hart et al, “Artificial Neural Network Modelling for Cryo-CMOS Devices”, *IEEE 14th Workshop on Low Temperature Electronics (WOLTE)*, April 2021.

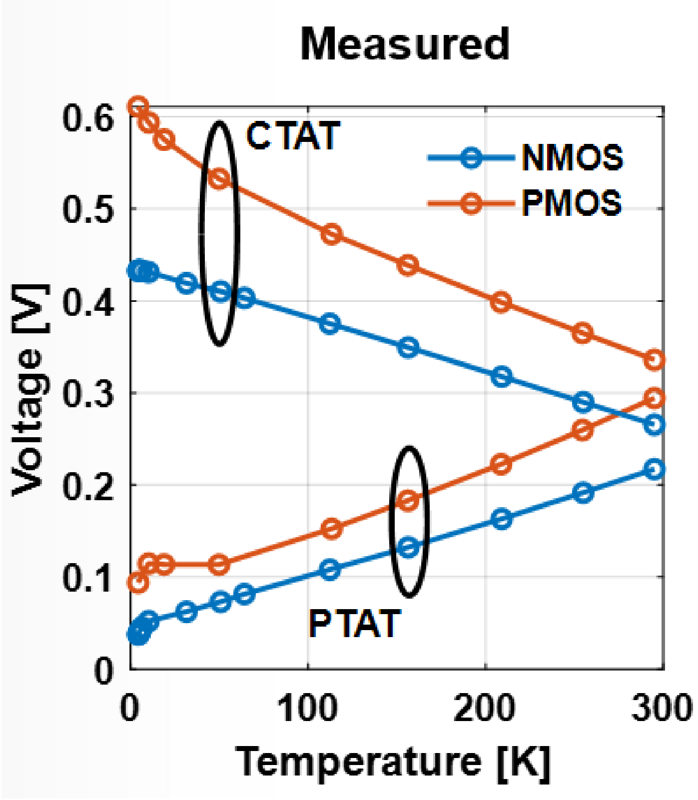
ANN for Cryogenic CMOS Modeling [3]

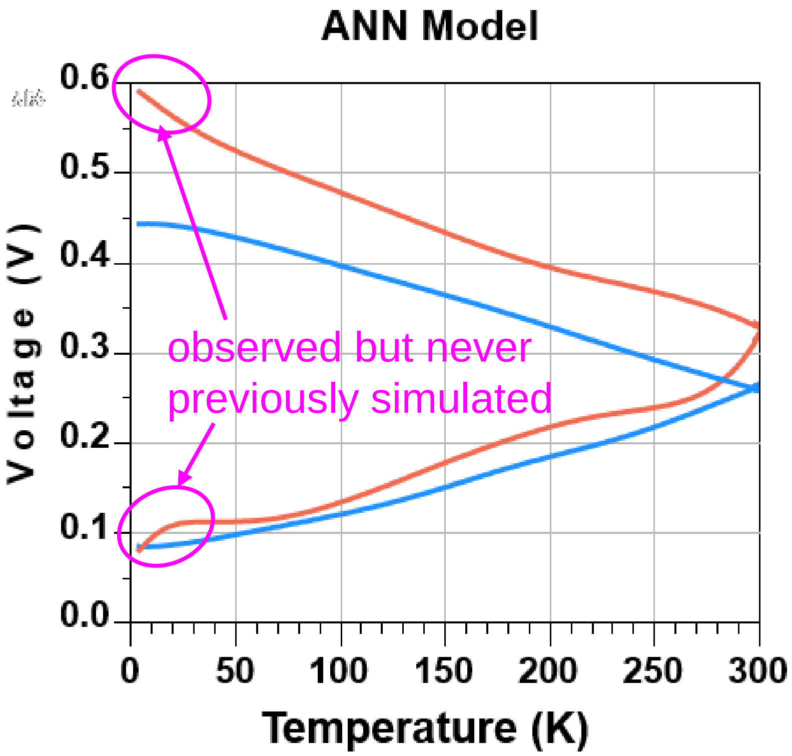
Voltage Reference Circuits



Keysight ADS implementation with ANN models







KEYSIGHT TECHNOLOGIES

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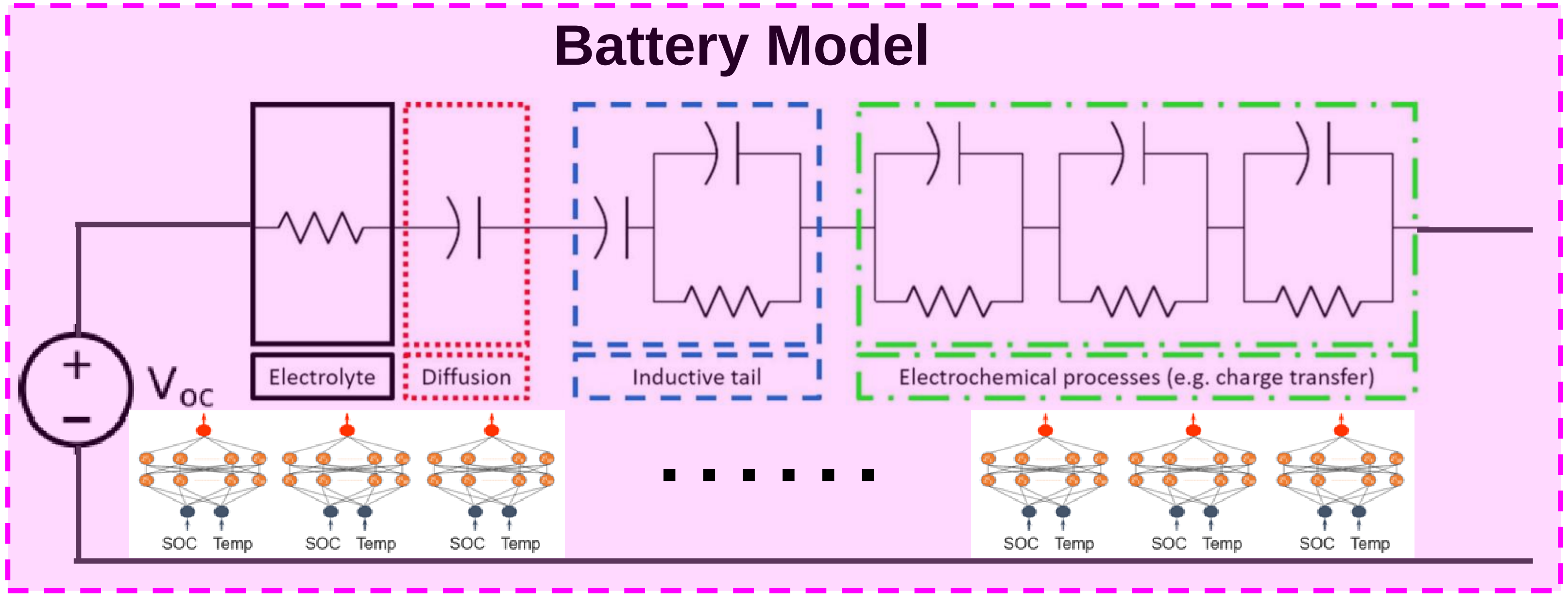
Battery Modeling [4]

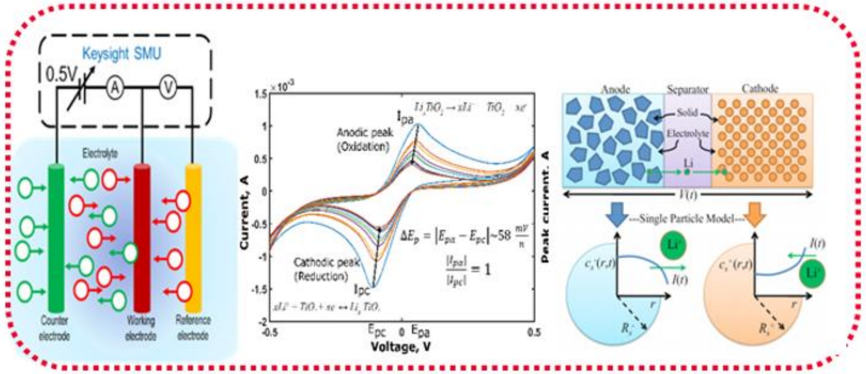


emulation

prediction / battery management system

parameter extraction / classification

electrochemical modelling



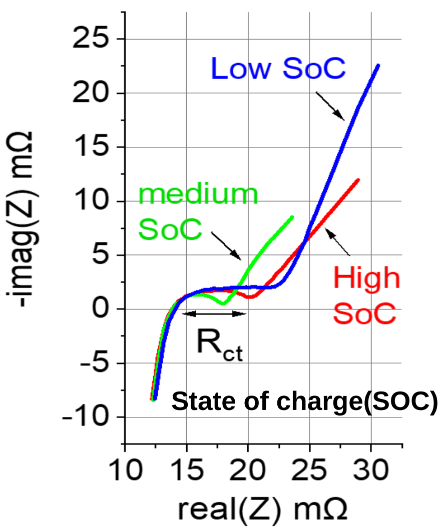
KEYSIGHT TECHNOLOGIES

[4] M. Kasper et al, "Calibrated Electrochemical Impedance Spectroscopy and Time-Domain Measurements of a 7 kWh Automotive Lithium-Ion Battery Module with 396 Cylindrical Cells", *Batteries & Supercaps published by Wiley-VCH GmbH*, 2022.

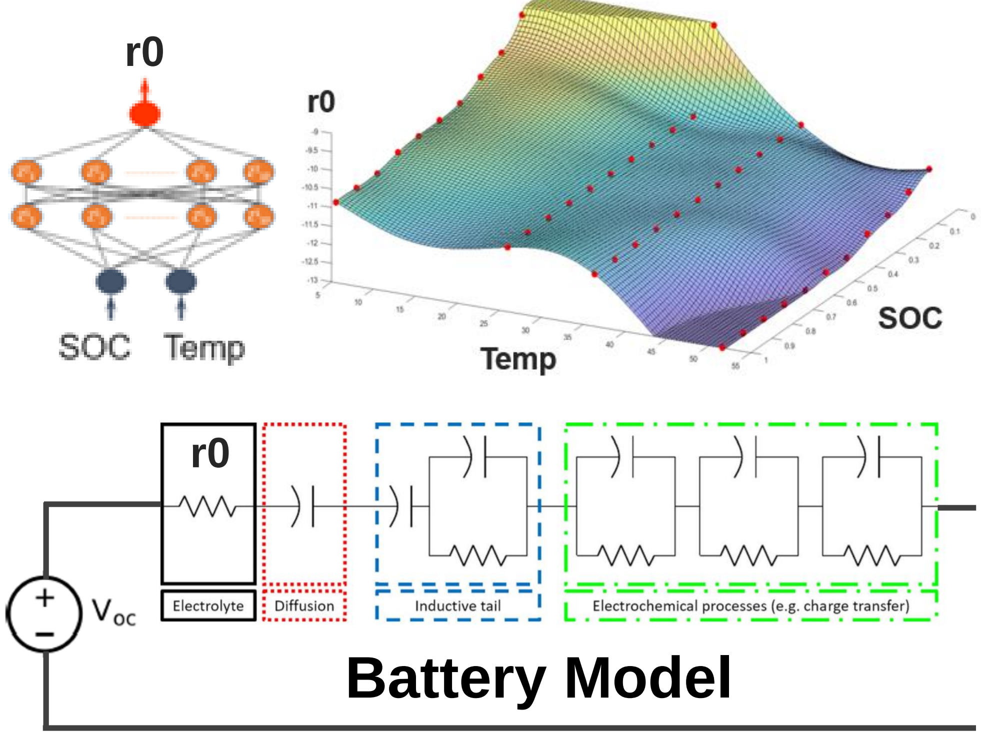
Battery Modeling [4]

Keysight Battery Test System

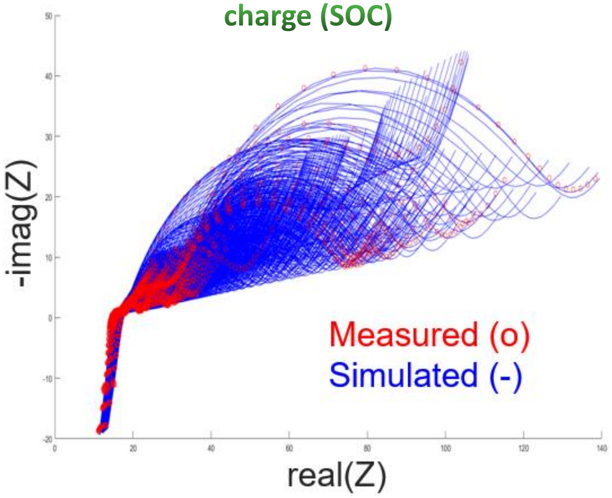
Electrochemical Impedance Spectroscopy (EIS)

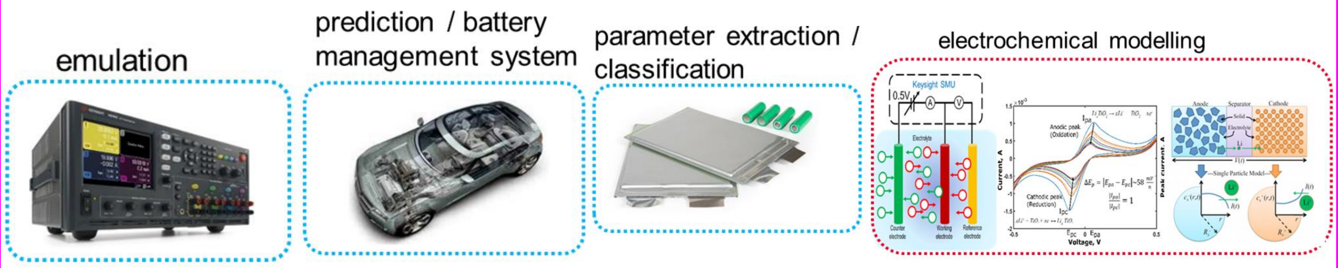


r0 = F(SOC, Temp)



Predicting the battery's behavior at different Temperature and State of charge (SOC)





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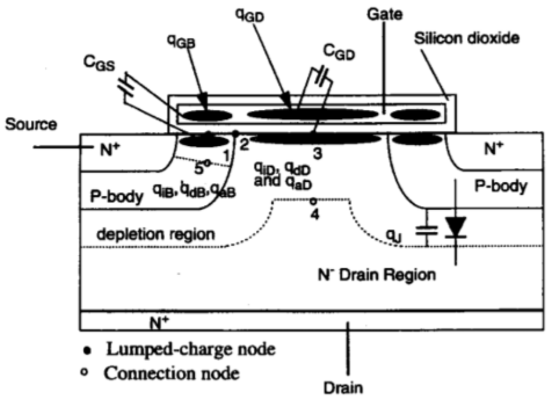
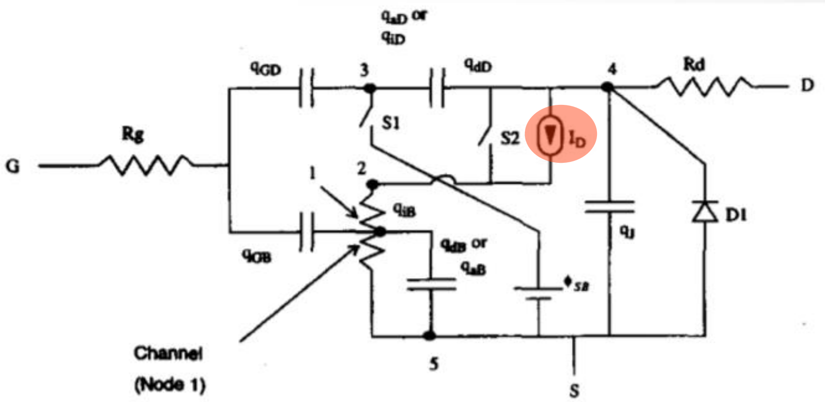
“Hybrid” physical – ANN modeling methodology [5]

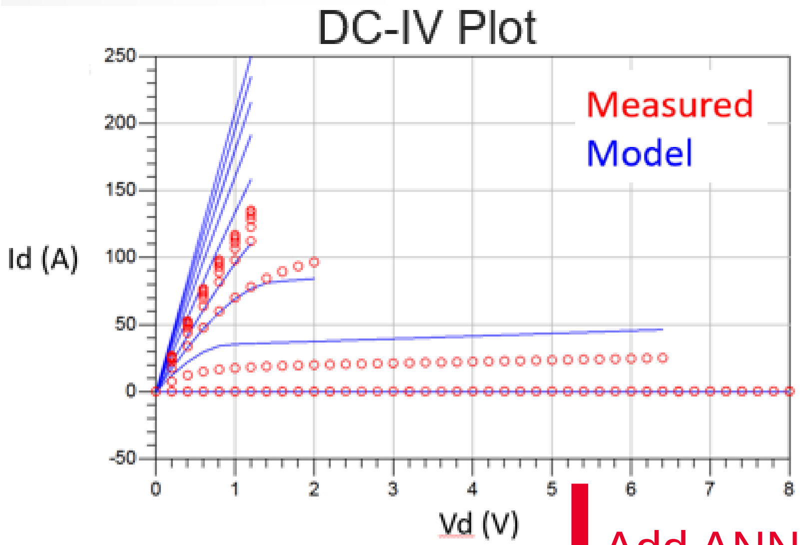
- maintains physics with increased accuracy

Power MOSFET



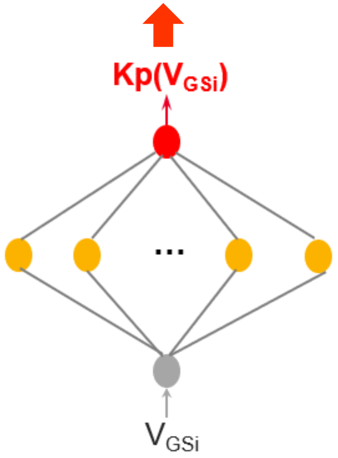
Physical Model

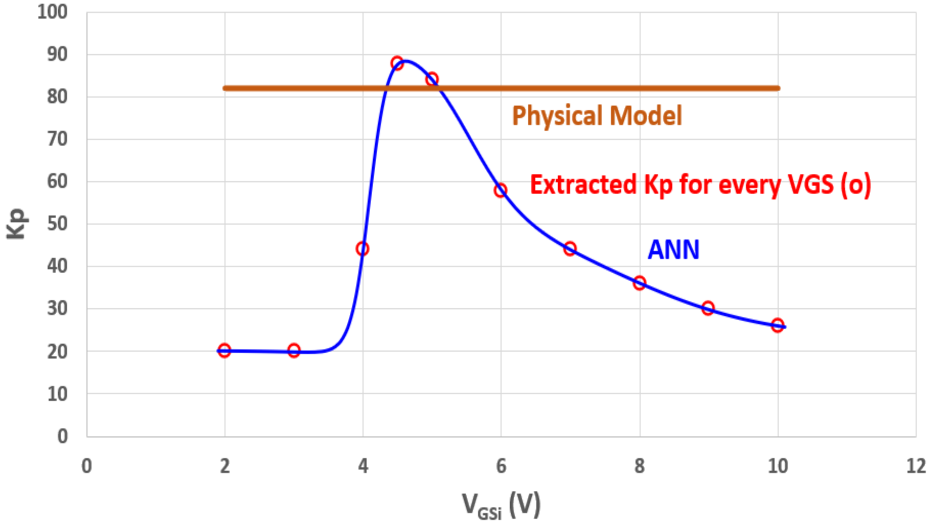


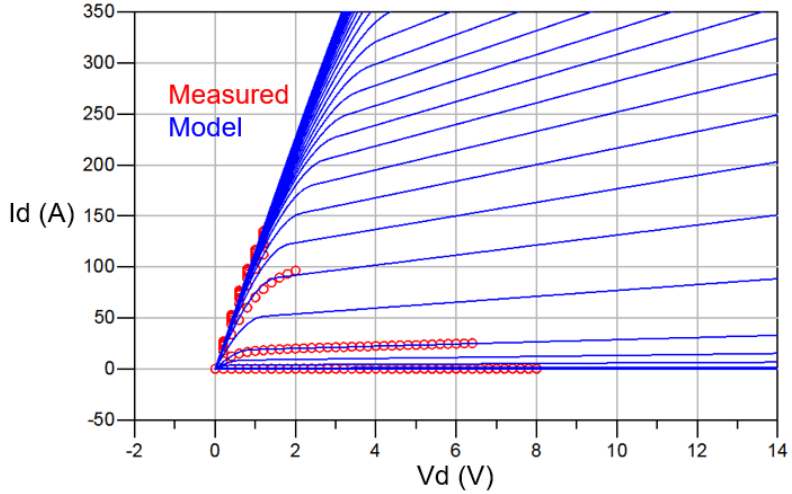


Add ANN

$$I_D = -((K_p/((1+v2s/V_{sat})*(1+theta*(V_{GSi}-VTB))))/C_{GSon})*qiB*v2s*(1+lda*V_{DSi}) - ddt(qj) - I(s,idd)$$







[5] IC-CAP, Keysight Technologies, Inc. https://www.keysight.com/us/en/lib/software-detail/computer-software/pathwave-device-modeling-iccap-software-2213548.html

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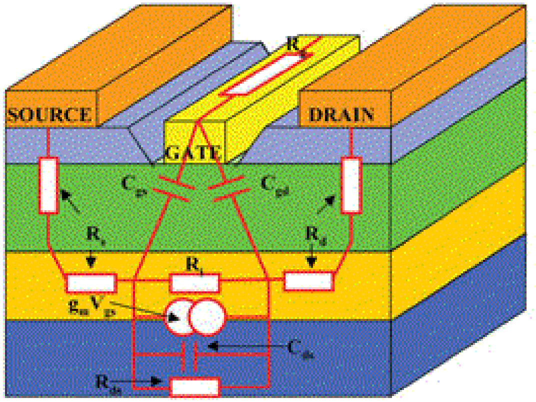
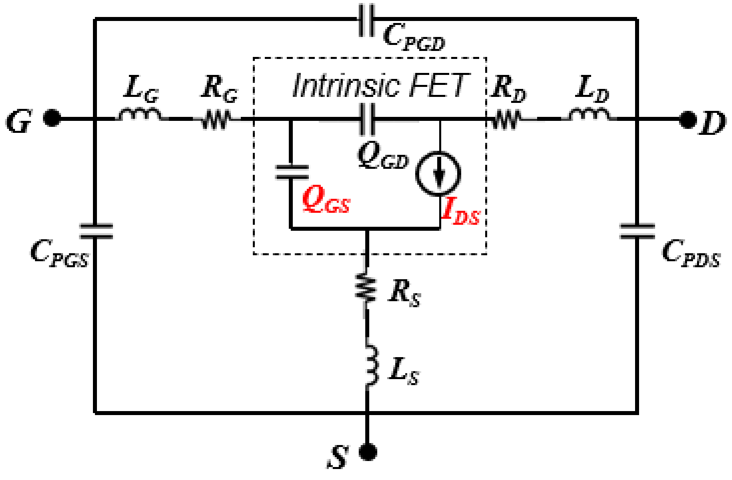
Behavioral Modeling

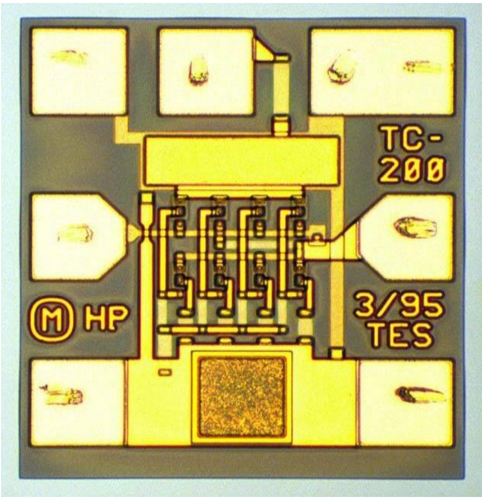


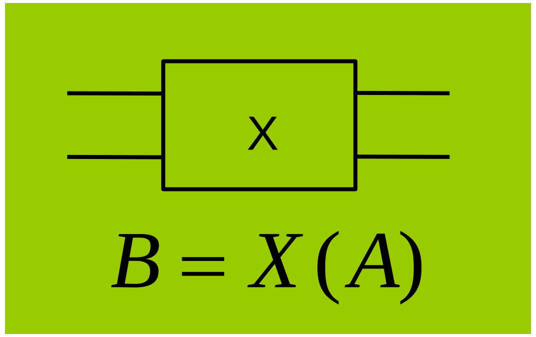


$$Q_{GS} = -C_{gs0} V_{bi} \left(1 - \frac{V_{GS}}{V_{bi}}\right)^{\eta}$$

$$I_{DS} = \left(\sum_{n=0}^{3} A_n \cdot V_{GS}^{n}\right) \cdot tanh(\gamma \cdot V_{DS})$$

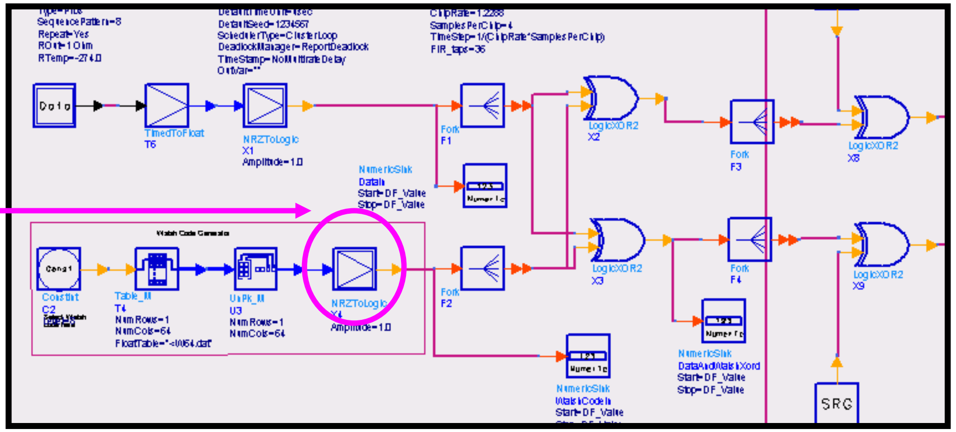
Device Model



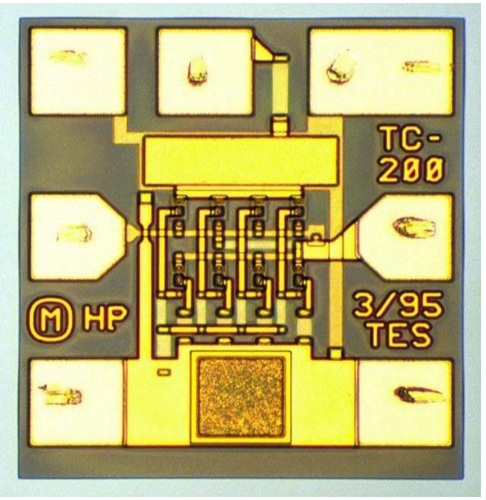


Behavioral Model

Design of Front End Module or IC



Behavioral Modeling

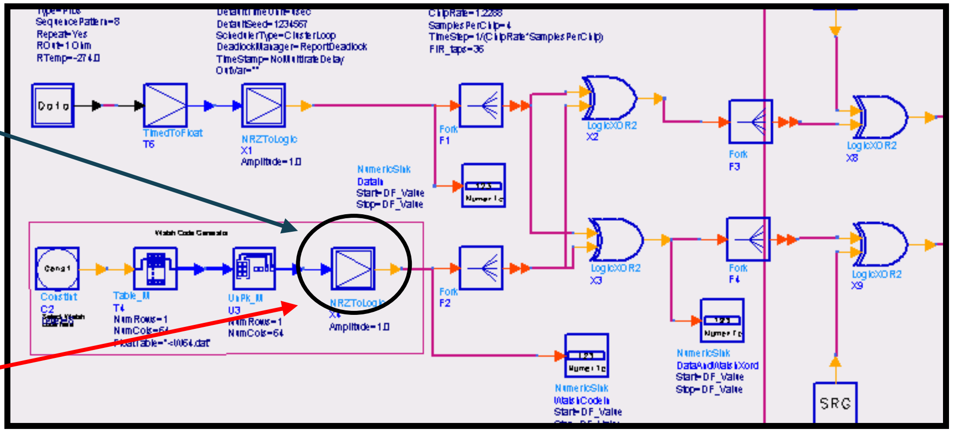


Actual Circuit

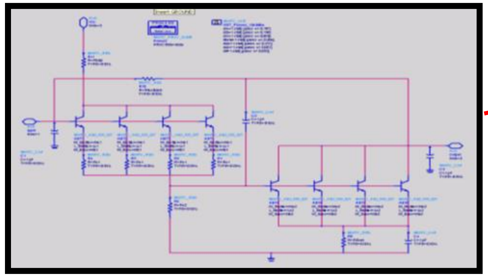
Measurement-Based Model

- Circuit model may not exist
- Circuit models may be inaccurate
- Completely protect design IP

Design of Front End Module or IC



Generate Behavioral Model



Detailed Circuit Model (SPICE/ADS) of IC

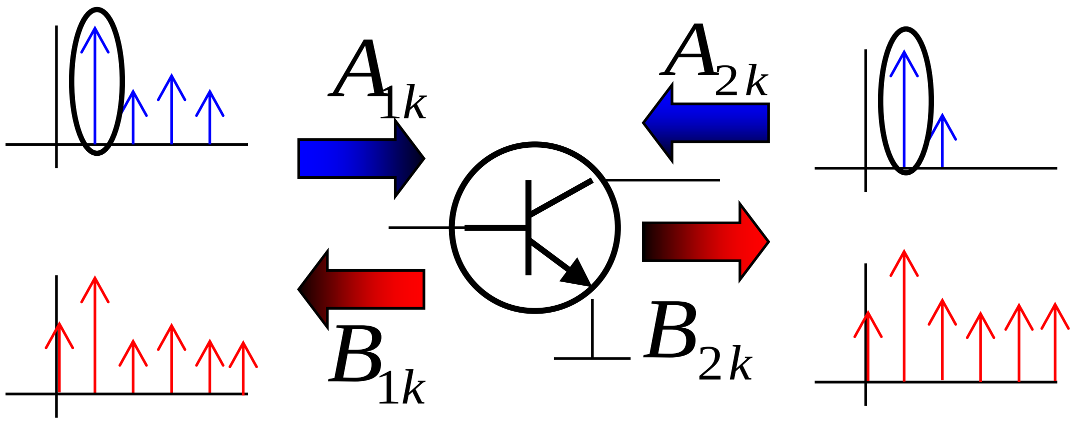
Simulation-Based Model

- Detailed circuit simulation is too slow
- Design system before building IC
- Completely protect design IP
- Do more in simulator than possible on instrument

KEYSIGHT TECHNOLOGIES

ANN for Frequency Domain Behavioral Modeling

Load-dependent X-parameter Model [6]



$$B = X(A)$$

$$B_{p,k} \cong X^{(F)}_{p,k}(LSOP)P^{k} + \sum_{(q,m)>(1,1)} X^{(S)}_{p,k;q,m}(LSOP)P^{k-m}A_{q,m} + \sum_{(q,m)>(1,1)} X^{(T)}_{p,k;q,m}(LSOP)P^{k+m}A^{*}_{q,m}$$

- Spectral linearization around *LSOP*=[*Bias, Freq,* $|A_{1,1}|$, *real*($A_{2,1}$), *imag*($A_{2,1}$)]
- $P = e^{j\phi(A_{11})}$ Phase of A11
- Outputs assuming all harmonics are matched
- Cross-frequency mismatch sensitivity terms

KEYSIGHT TECHNOLOGIES

[6] D. E. Root et al, "X-Parameters, Characterization, modeling, and design of nonlinear RF and microwave components," Cambridge University Press, 2013.

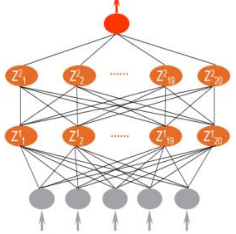
ANN for Frequency Domain Behavioral Modeling

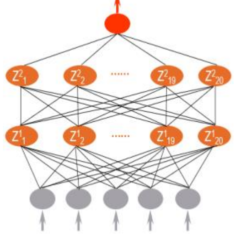
$$B_{p,k} \cong X^{(F)}_{p,k}(LSOP)P^{k} + \sum_{(q,m)>(1,1)} X^{(S)}_{p,k;q,m}(LSOP)P^{k-m}A_{q,m} + \sum_{(q,m)>(1,1)} X^{(T)}_{p,k;q,m}(LSOP)P^{k+m}A^{*}_{q,m}$$

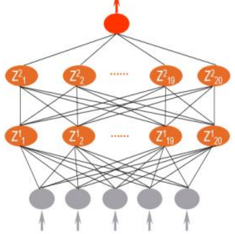
VDC	Freq	|A1,1|	Real(A2,1)	Imag(A2,1)	Real(XF2,1)
2.0	1e9	0.0375	0.0316	-0.123	0.0315
5.0	2e9	0.0467	0.1643	-0.588	0.1041
8.0	3e9	0.1470	0.5623	-0.963	-0.3162
…	…	…	…	…	…

VDC	Freq	|A1,1|	Real(A2,1)	Imag(A2,1)	Real(XS2,1,2,3)
2.0	1e9	0.0375	0.0316	-0.123	0.0015
5.0	2e9	0.0467	0.1643	-0.588	0.2102
8.0	3e9	0.1470	0.5623	-0.963	-0.1116
…	…	…	…	…	…

VDC	Freq	|A1,1|	Real(A2,1)	Imag(A2,1)	Real(XT2,1,2,3)
2.0	1e9	0.0375	0.0316	-0.123	-0.6031
5.0	2e9	0.0467	0.1643	-0.588	-0.5104
8.0	3e9	0.1470	0.5623	-0.963	0.2316
…	…	…	…	…	…







Current limitations:

- Gridded data structure forces high volume of data measurement, some conditions are hard or difficult (device damage) to measure
- Accurate simulation requires a large table of data
- Time to load data file is long and Memory usage is large
- Results may depend on particular simulator capabilities to read tables and interpolation algorithms

Benefits of replacing tables with ANNs:

- Data can be taken as needed for accuracy (e.g., adaptively) and as may be constrained by device operation
- Discrete data is converted to smooth functions for further applications downstream (optimization, system simulation, hierarchical modeling, Digital Twin)

Downside of ANNs for X-parameter modeling:

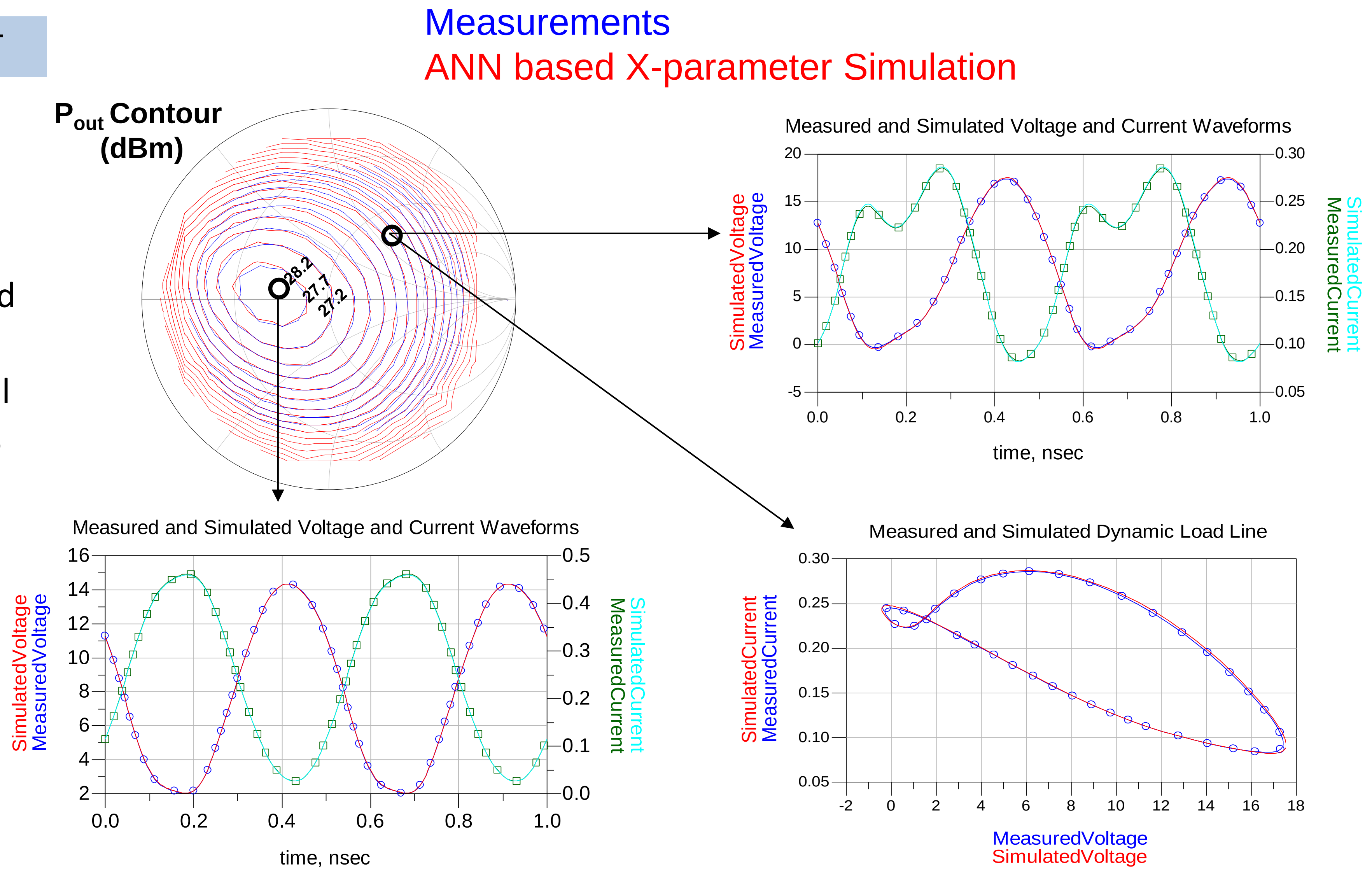
- Training times may be long, requiring parallel training infrastructure (Keysight unpublished work)

ANN for Frequency Domain Behavioral Modeling

WJ FP2189 1W HFET

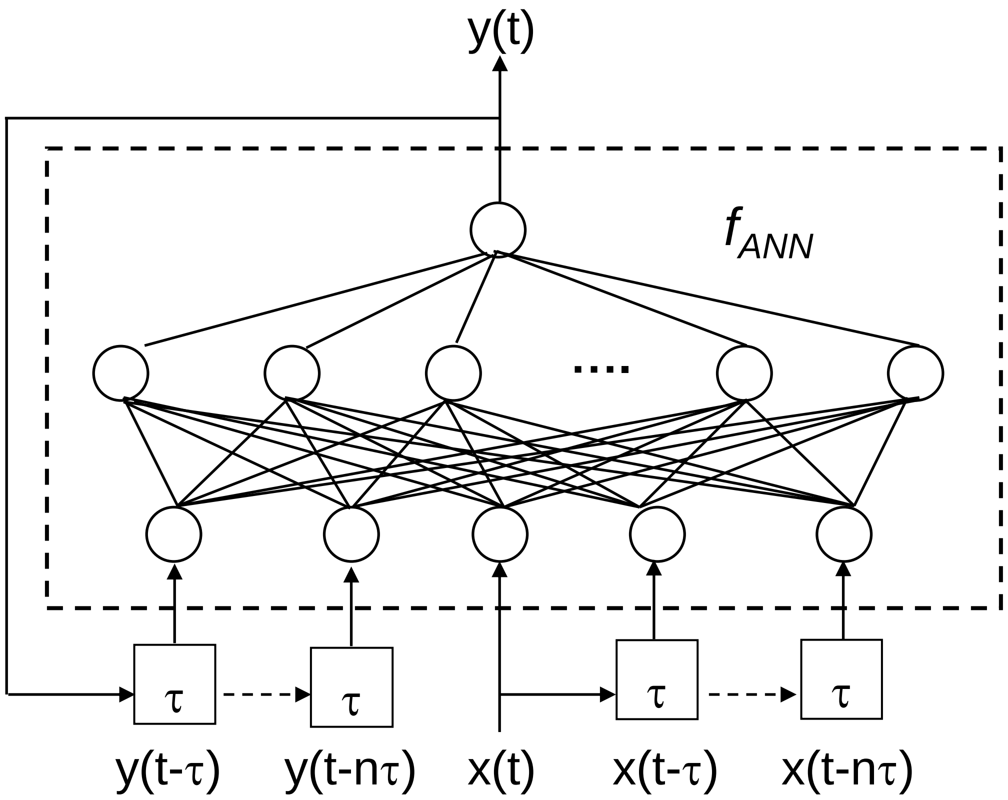
Model Validations
fund=2GHz, @Vd=8V,
Id=250mA, Pin=12dBm

The results of unpublished ANN-based X-parameter model is virtually identical to the table-based results first published [8] shown in these plots.



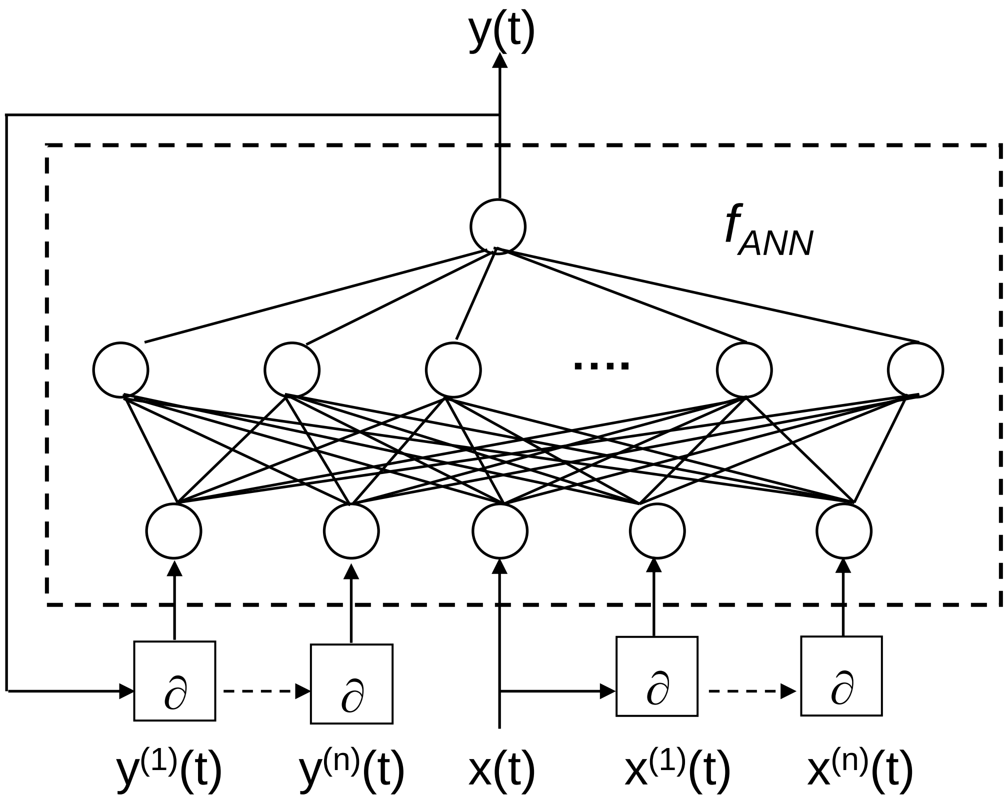
[6] D. E. Root et al, “X-Parameters, Characterization, modeling, and design of nonlinear RF and microwave components,” Cambridge University Press, 2013.

ANN for Time Domain Behavioral Modeling



Recurrent Neural Network (RNN)

$$y(t) = f_{ANN}(y(t-\mathrm{\tau}), \ldots, y(t-\mathrm{n\tau}), x(t), x(t-\mathrm{\tau}), \ldots ,x(t-\mathrm{n\tau}))$$

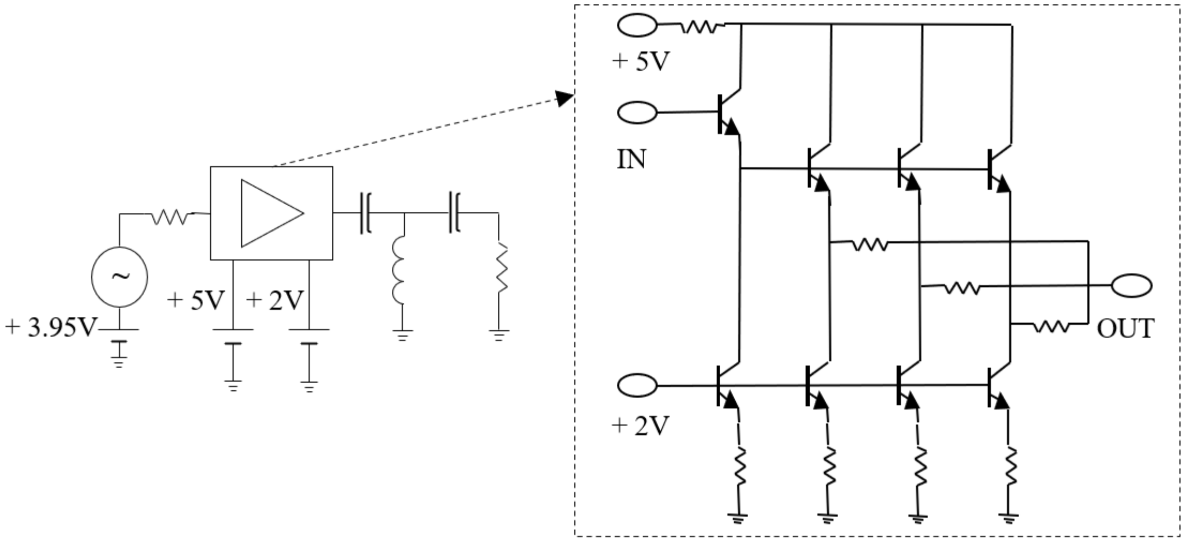


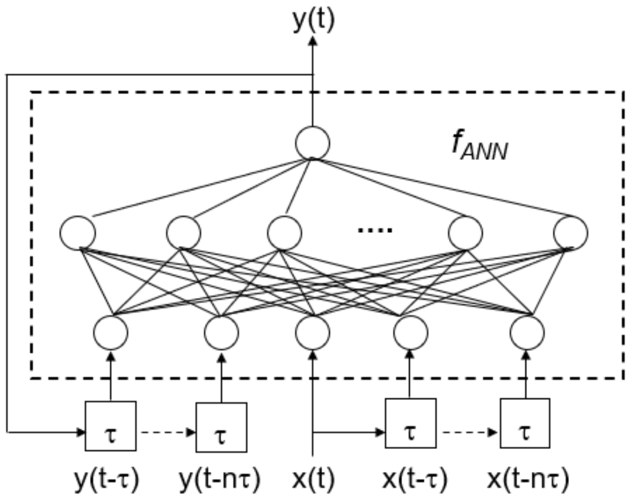
Dynamic Neural Network (DNN)

$$y(t) = f_{ANN}(y^{(1)}(t), \ldots ,y^{(n)}(t), x(t), x^{(1)}(t), \ldots ,x^{(n)}(t))$$

KEYSIGHT TECHNOLOGIES

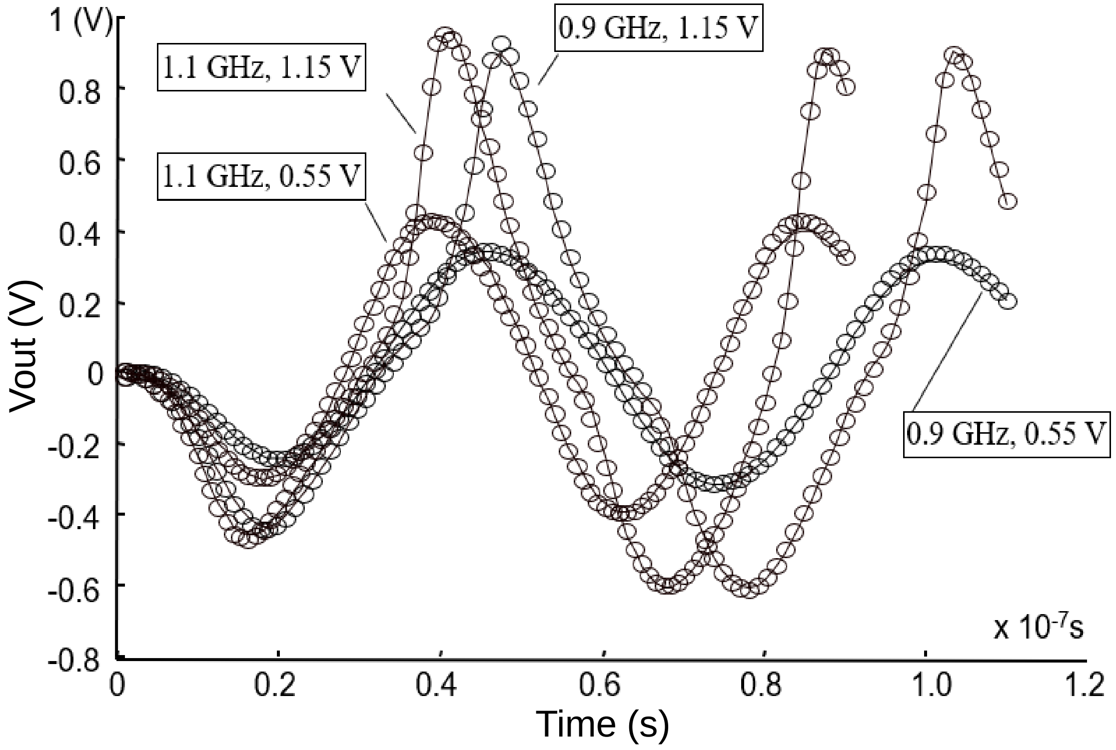
ANN for Time Domain Behavioral Modeling [7]





Recurrent Neural Network (RNN)

(o) Original PA
(-) RNN model



	RNN Model	Original PA
CPU Time for evaluation of 900 different sets of input–output waveforms	10 seconds	177 seconds

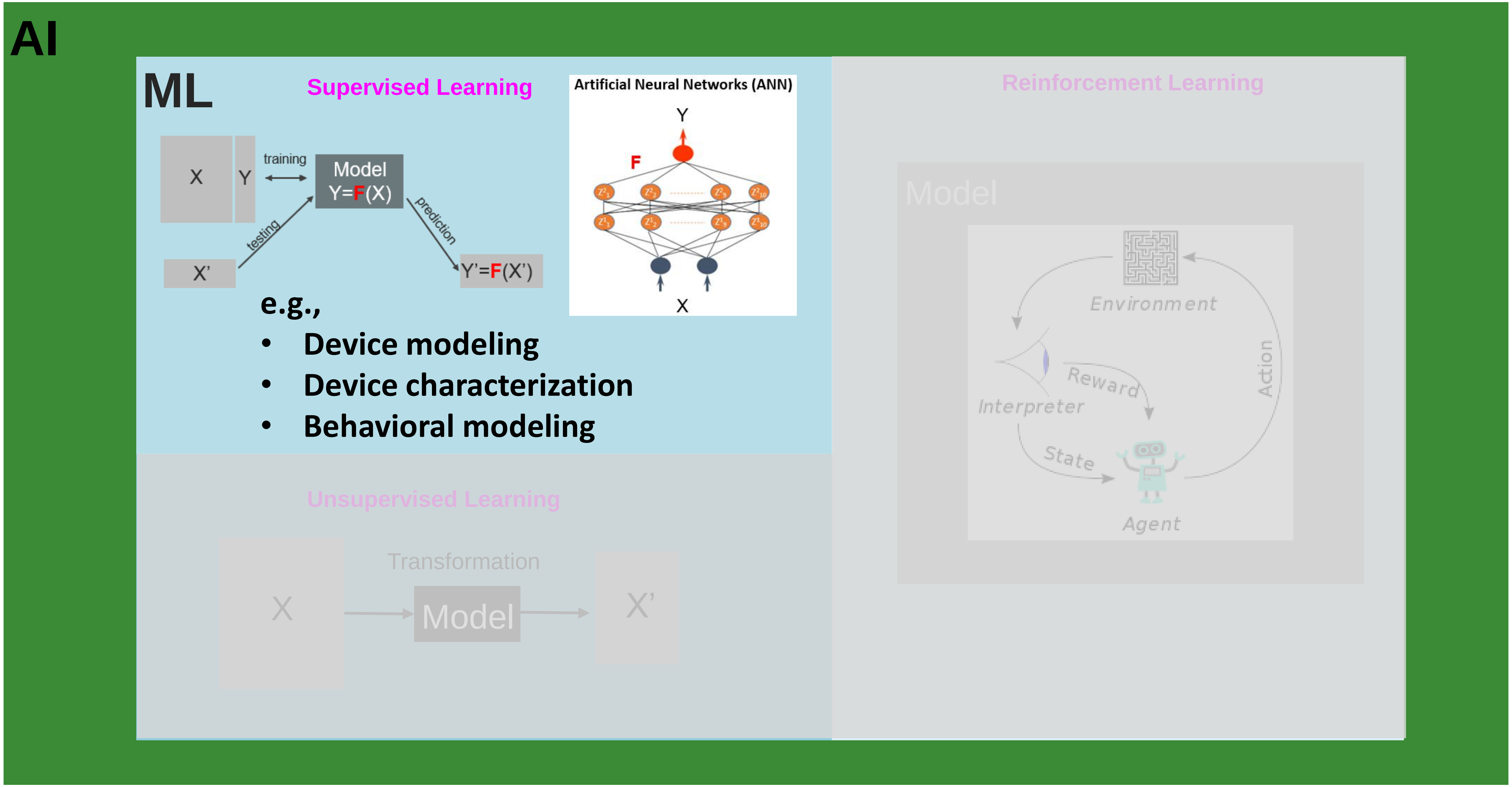
KEYSIGHT TECHNOLOGIES

[7] Y.H. Fang et al, "A new macromodeling approach for nonlinear microwave circuits based on recurrent neural networks," *IEEE Trans. Microw. Theory Tech*, vol. 48, pp. 2335–2344, Dec. 2000.

Outline

- Introduction to AI, ML and ANN
- ANN for electronic device modeling
- ANN for electronic behavioral modeling
- **Summary**

Summary



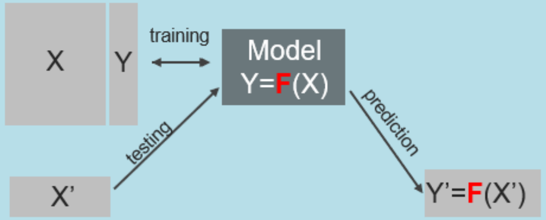
AI
ML
Supervised Learning
X
Y
training
Model
Y=F(X)
testing
X'
prediction
Y'=F(X')
Artificial Neural Networks (ANN)
Y
F
X
e.g.,
• Device modeling
• Device characterization
• Behavioral modeling
Unsupervised Learning
Transformation
X
Model
X'
Reinforcement Learning
Model
Environment
Reward
Interpreter
Action
State
Agent

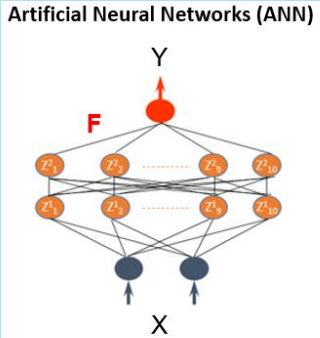
Summary

AI

ML

Supervised Learning

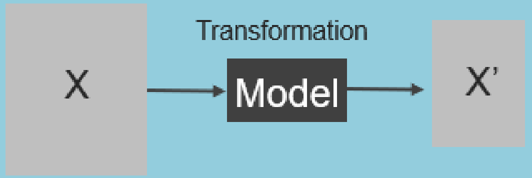




e.g.,

- **Device modeling**
- **Device characterization**
- **Behavioral modeling**

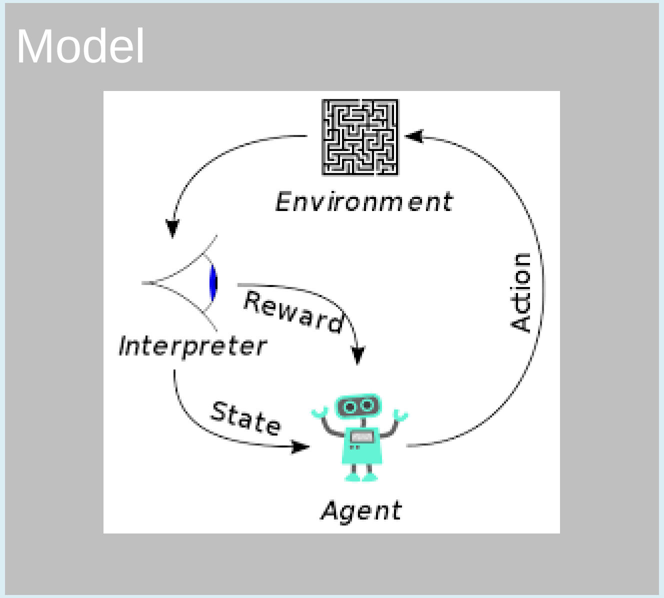
Unsupervised Learning



e.g.,

- **Automatic Circuit Tuning**
  Automates the post-fabrication circuit tuning process

Reinforcement Learning



e.g.,

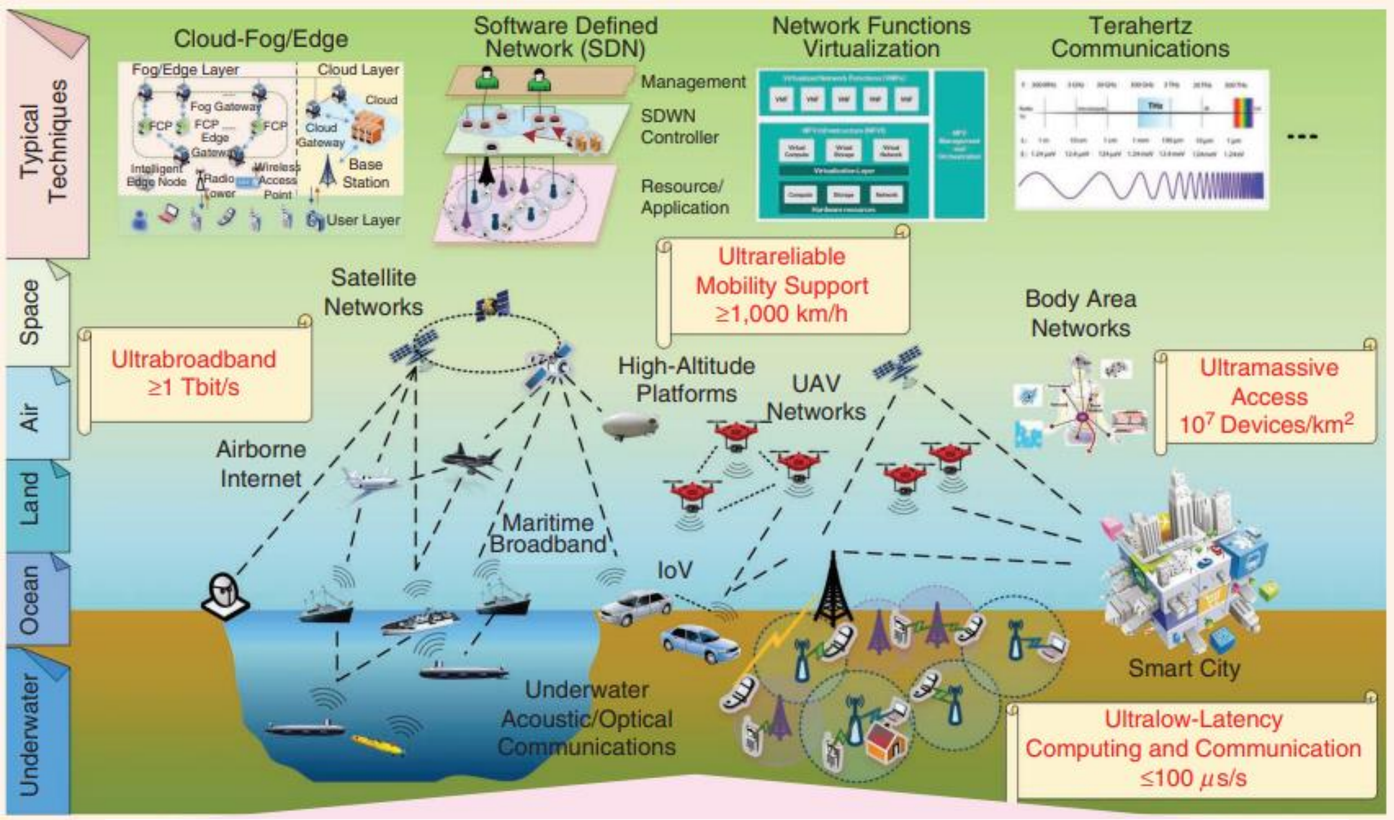
- **Optimization and multi-physics**
  Exploration and exploitation for design problems with many variables

KEYSIGHT TECHNOLOGIES

Future Potential

AI

ML



6G Network [8]

- Make more optimized and adaptive data-driven decisions
- Alleviate communication challenges
- Meet requirements from emerging services

KEYSIGHT TECHNOLOGIES

[8] J. Du et al, "Machine Learning for 6G Wireless Networks: Carrying Forward Enhanced Bandwidth, Massive Access, and Ultrareliable/Low-Latency Service", *IEEE Vehicular Technology Magazine*, vol. 15, pp. 122-134, Dec. 2020.

Thank you!