First Experiences in Modeling using an Artificial Neural Network

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Machine Learning Overview

Machine learning
- Is a sub-field of Artificial Intelligence (AI)

supervised
- Needs labeled training data
- Makes predictions

unsupervised
- Does not need labeled training data
- Finds hidden pattern in data

classification
- Learning on a labeled data set, e.g. detection of spam emails

regression
- Learning on data with continuous targets, e.g. stock price prediction, weather forecast

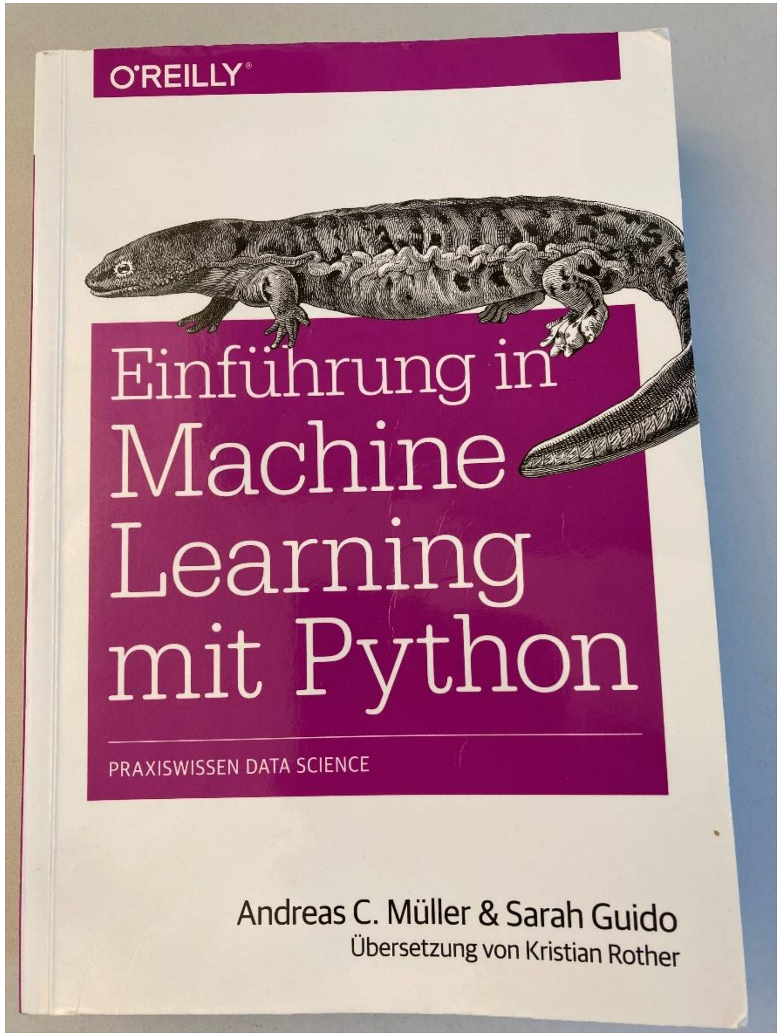
clustering
- Grouping similarities
- E.g. find all pictures with houses, cars, elephants

association
- Looking for relationship in data, e.g. customers who have bought a hammer often by a plaster (at amazon)

dim. reduction
- E.g. noise removal

Books

- There are several book for ML beginners using python
- This one uses the package scikit-learn and is easy to understand
- Also English version available (German is a translation)
- Many other books available with different software packages for ML, e.g. TensorFlow, Keras and PyTorch



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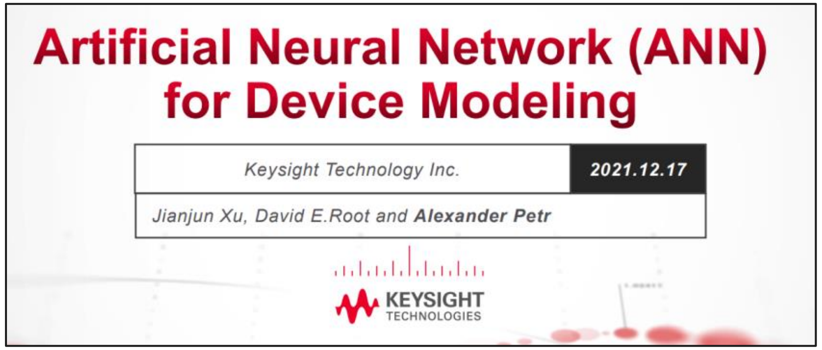
Why using Machine Learning Method for Compact Modeling?

Possible Benefits

– Automatic model generation
– For devices where no compact model exists
– Independent of any compact model implementation in different simulators

Presentation on MOS-AK 2019



Starting Point

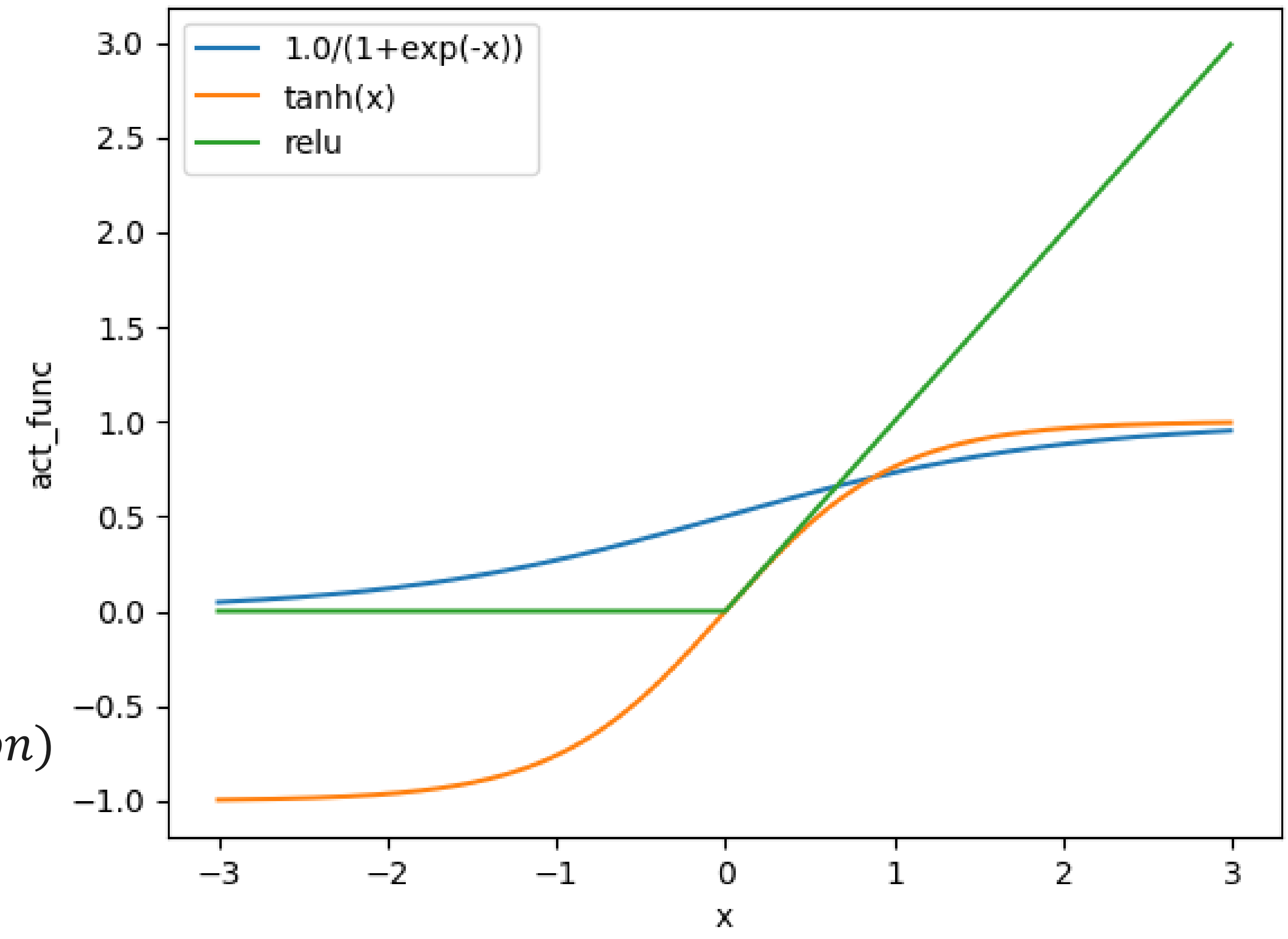
– Example in ICCAP/2023
– ANN model translated to VerilogA model

Activation functions

$$f(x) = \tanh(x)$$
$$(tanhyp\ function)$$

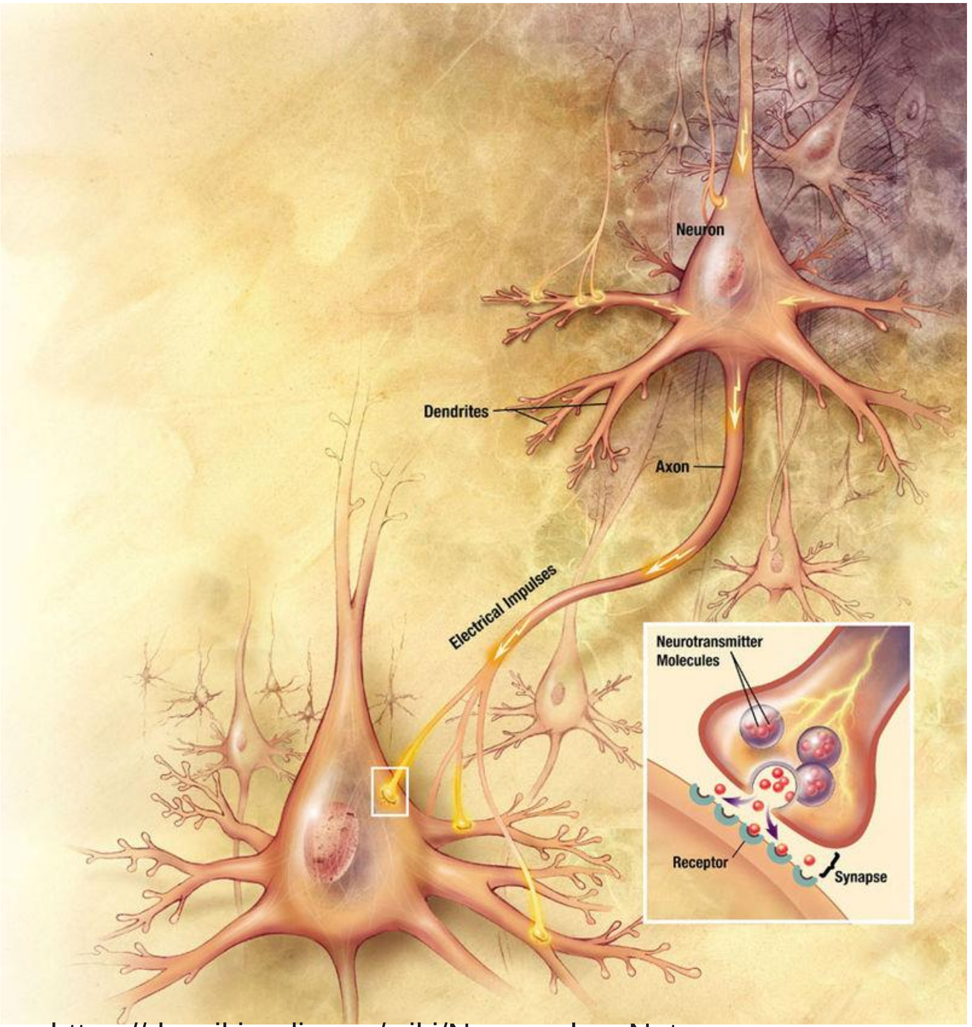
$$f(x) = \frac{1}{1 + e^{-x}}$$
$$(sigmoid\ or\ logistic\ function)$$

$$f(x) = \max(0, x)$$
$$(RELU = rectified\ linear\ unit\ function)$$



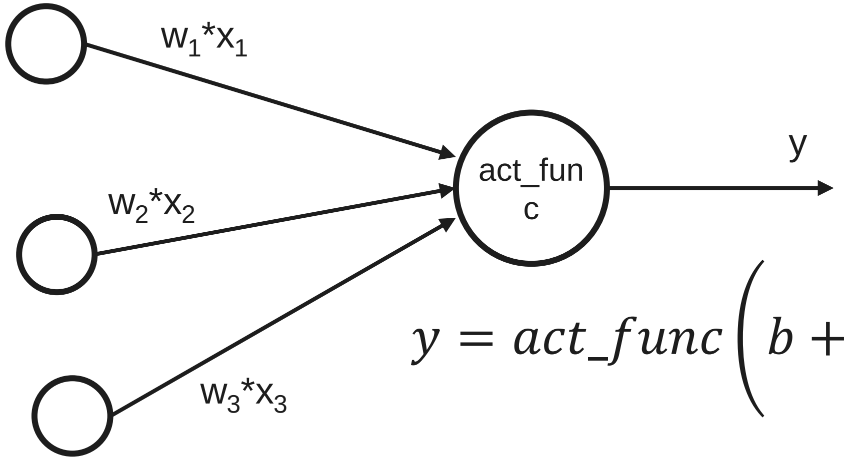
Neuronal network (NN)

Neuronal network



https://de.wikipedia.org/wiki/Neuronales_Netz

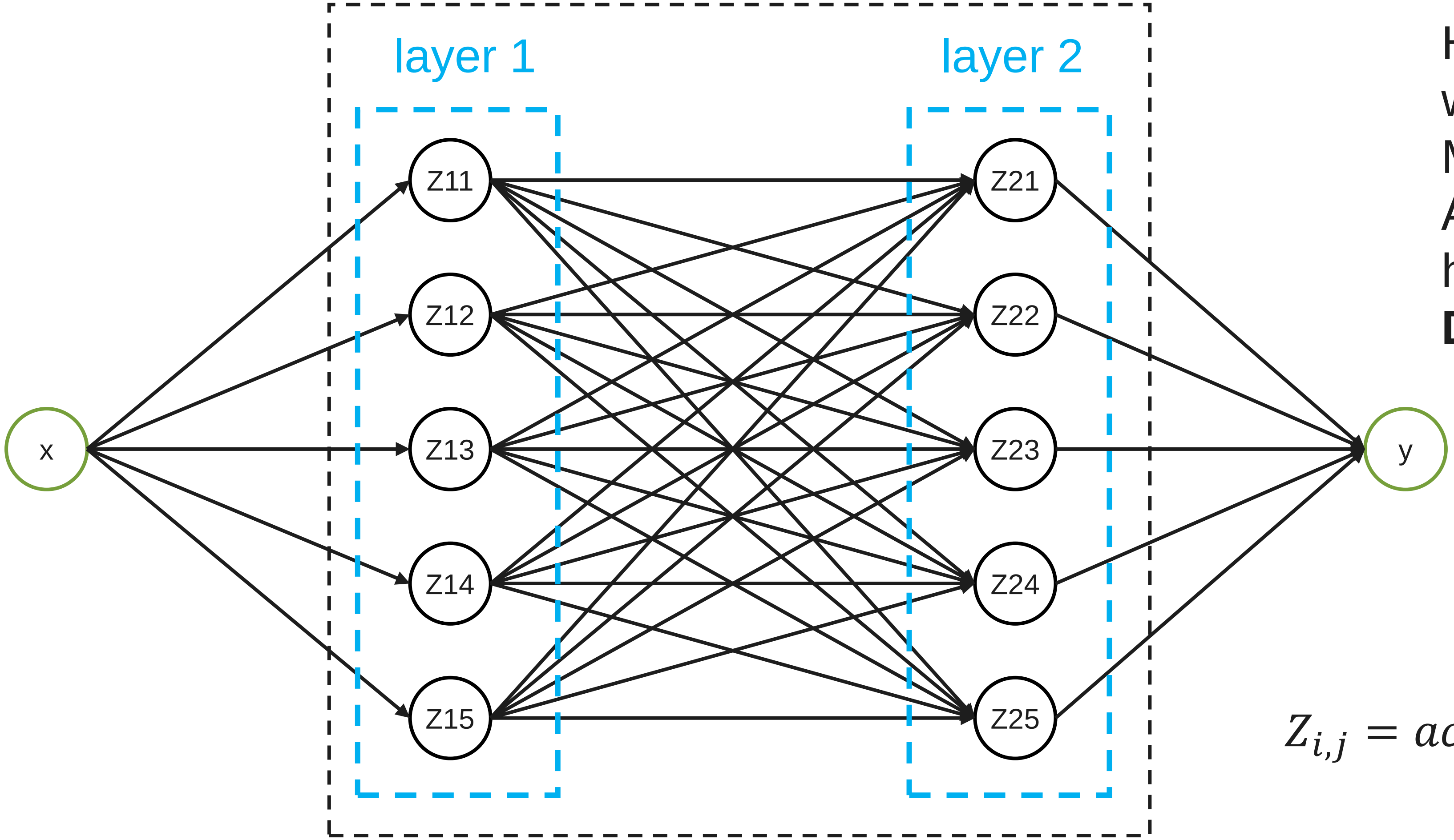
Artificial Neuronal network=ANN



$$y = act\_func\left(b + \sum_{k=0}^{n} w_k x_k\right)$$

A neuron is represented by a formula (act_func). The neuron is weighting the inputs (w_i) and if its own threshold value (b) is reached it passes a signal to the output y.

Artificial neural network (ANN) example



Here: 2 hidden layers with 5 neurons each. Machine Learning with ANN's with more than 3 hidden layers are called **Deep Learning**.

$$Z_{i,j} = act\_func\left(b_{i,j} + \sum_{k=0}^{n} c_{i,j,k} Z_{i-1,k}\right)$$

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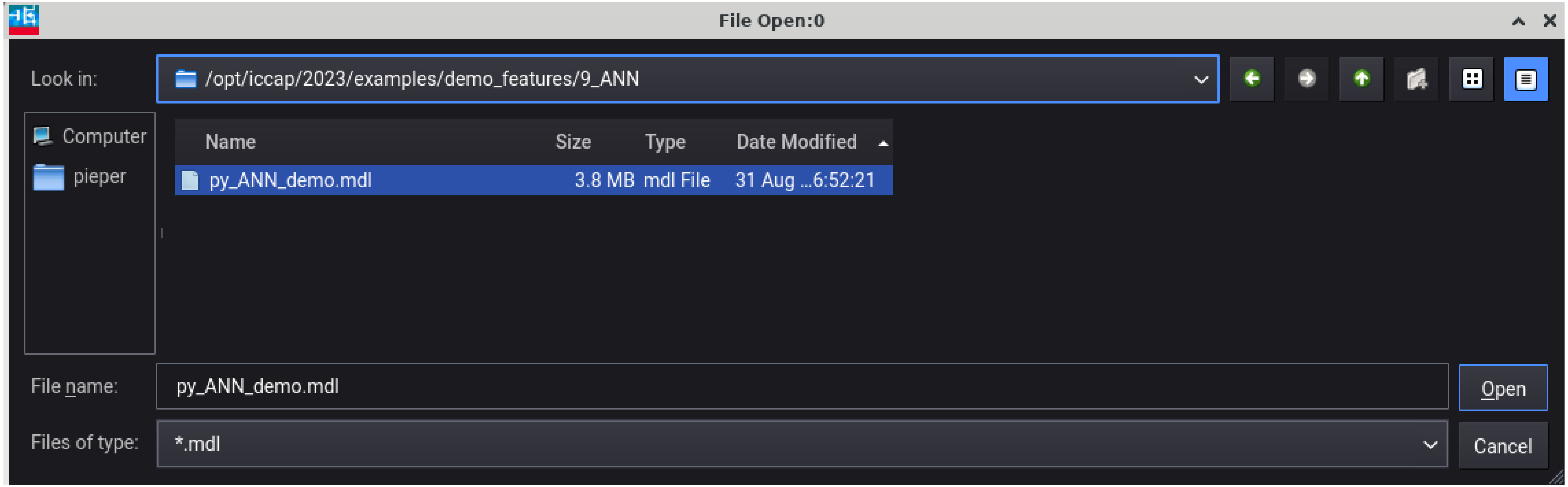
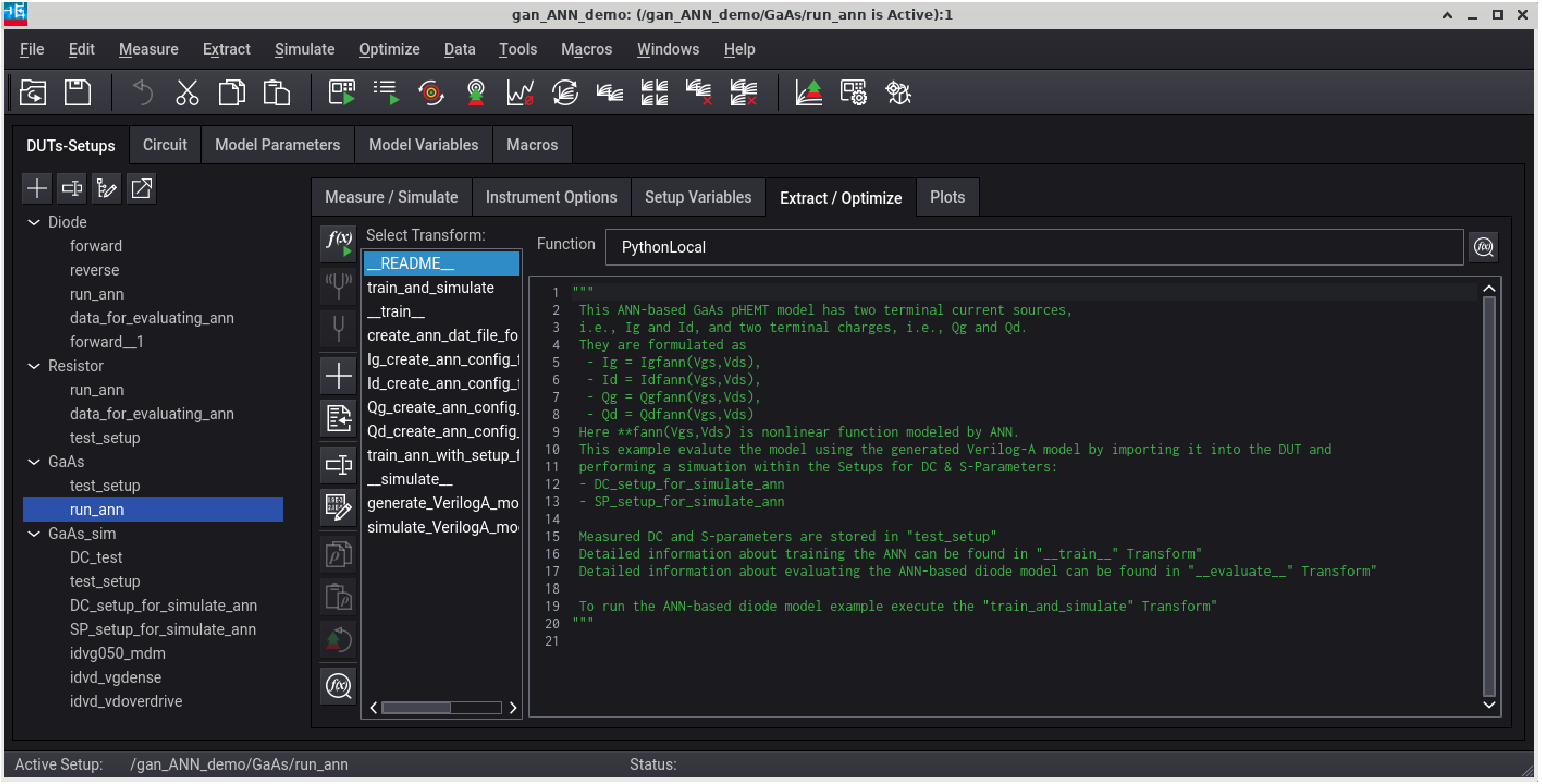
ANN Model for Semiconductor Devices

– ICCAP .mdl file is available in the ICCAP examples directory



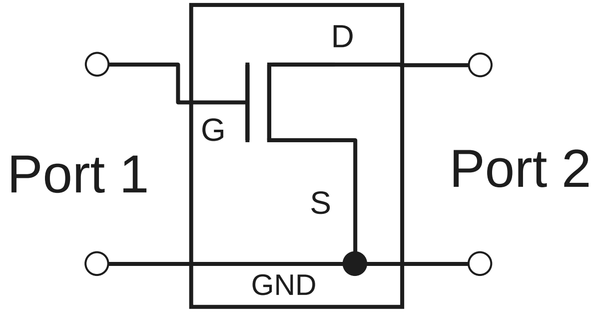
ICCAP model generator



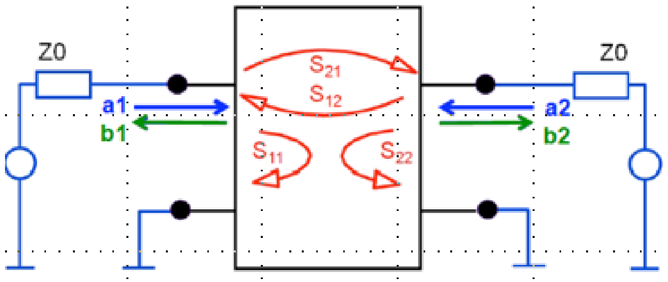
Training Setup File

ANN information:
(1) #inputs
2
(2) #outputs
1
(3) #layers
2
(4) #neurons per layer
14
(5) neuron activation function (options: **Sigmoid, HyperbolicTangent, RELU**)
HyperbolicTangent
(6) training type (options: 1, 2, 3 options: 1 (x,y), 2 (x, y, dy/dx))
2
(7) read ANN weights from a file
NULL
(8) Action (options: 1 (train), 2 (simulate), 3 (classify))
1
(9) Data file used in action
ANN_GaAs_Id.dat
(10) Max #Iterations
2000
(11) Stop Tolerance
0.0
(12) Training error weighting file
ANN_GaAs_Id_error_weighting.dat
(13) Output file name
ANN_GaAs_Id
(14) Ouput format (options: 1(text formula), 2(verilog-A format), 3(.struc and .scale), 4(text, verilog-A, .struc))
4
****

Generating ML data for Type 2



Measurement/Simulation



S-parameters

$$b_1 = S_{11} * a_1 + S_{12} * a_2$$
$$b_2 = S_{21} * a_1 + S_{22} * a_2$$

Y-parameters

$$\begin{pmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{pmatrix}$$

ML data

$$\frac{\partial Q_D(V_D, V_G)}{\partial V_G} = \frac{imag(Y_{21})}{\omega}$$

$$\frac{\partial Q_D(V_D, V_G)}{\partial V_D} = \frac{imag(Y_{22})}{\omega} = C_{OSS}$$

$$\frac{\partial Q_G(V_D, V_G)}{\partial V_G} = \frac{1}{imag\left(\frac{1}{Y_{11}}\right)\omega} = -C_{ISS}$$

$$\frac{\partial Q_G(V_D, V_G)}{\partial V_D} = \frac{imag(Y_{12})}{\omega} = C_{RSS}$$

$$\omega = 2\pi f$$

ICCAP Example: ANN VerilogA Diode Model

```
`include "disciplines.vams"
`include "constants.vams"


module diode_ann_va(a,c);

//
//  Node definitions
//
inout a,c;
electrical a,c;

parameter real powerscale=5.0;

`include "ANN_Diode2.inc"

real vdio, idio;

analog begin
   vdio=V(a,c);
   I(a,c) <+ vdio*ANN_Diode(vdio)**powerscale;
end
endmodule
```

The ANN_Diode model describes not the diode current directly but the conductance of the diode.

Calculation of current by rescaling the model

ICCAP Example: VerilogA ANN function

```
function real ANN_Diode;
   input V1;
   real V1;
   real x0,z1_0, z1_1, z1_2, z1_3, z1_4, z2_0, z2_1, z2_2, z2_3, z2_4, ys0;
   begin
      x0 = (-1.0+2.0*(V1-(-8.0))/9.0);

      z1_0 = 1.0/(1.0+exp(-((-56.4793825193895)+56.83606977770033*x0)));
      z1_1 = 1.0/(1.0+exp(-(1.504732767164275+(-4.049932605696579)*x0)));
      z1_2 = 1.0/(1.0+exp(-(29.86924866880653+(-8.144433686817834)*x0)));
      z1_3 = 1.0/(1.0+exp(-((-17.17578381186036)+5.839141465946761*x0)));
      z1_4 = 1.0/(1.0+exp(-(30.63527142706413+(-36.9325279221443)*x0)));

      z2_0 = 1.0/(1.0+exp(-((-6.41024828)+15.88711934*z1_0+(-1.69276195)*z1_1+11.2775154*z1_2+(-5.15566913)*z1_3+2.44111535*z1_4)));
      z2_1 = 1.0/(1.0+exp(-((-17.7679139)+0.0263055772*z1_0+21.9485589*z1_1+15.1785773*z1_2+(-19.1315197)*z1_3+51.2889828*z1_4)));
      z2_2 = 1.0/(1.0+exp(-(12.4787284+1.54029617*z1_0+(-5.03645648)*z1_1+3.59705252*z1_2+4.93573320*z1_3+12.3734043*z1_4)));
      z2_3 = 1.0/(1.0+exp(-(0.631534734+(-11.6696915)*z1_0+(-8.34907317)*z1_1+(-10.7948479)*z1_2+3.08682062*z1_3+(-12.5097810)*z1_4)));
      z2_4 = 1.0/(1.0+exp(-((-4.41800986)+152.019283*z1_0+(-10.2127767)*z1_1+8.43921304*z1_2+(-9.20073518)*z1_3+19.6770781*z1_4)));

      ys0 = 5.74399943+(-9.95798928)*z2_0+(-1.42303571)*z2_1+18.3086737*z2_2+2.92343483*z2_3+(-12.6791333)*z2_4;
      ANN_Diode = 0.00584248683+ys0*(0.521889270);

   end
endfunction // ANN_Diode
```

weights
thresholds
scaling of input x and output y

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Training and Test Data

Device

– 40V LDMOS, 1 geometry and room temperature only
– Data generated by simulation by SPICE simulation with a compact model

Test data

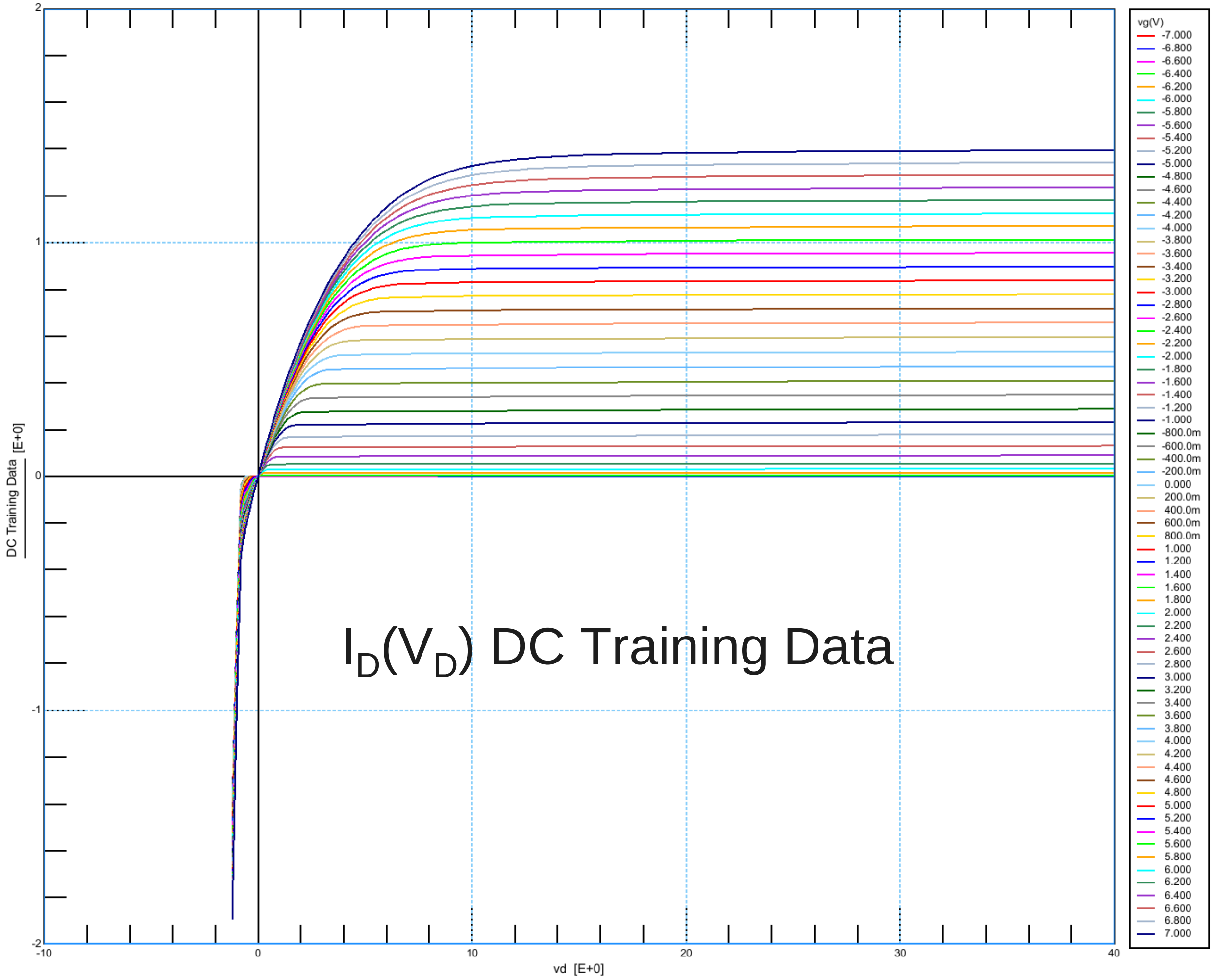
– ID(VGS=-7V, …,7V, step=**100mV**; VDS=-1V, …,40V, step=**100mV**)
– 411*141=57951 data points

Training data

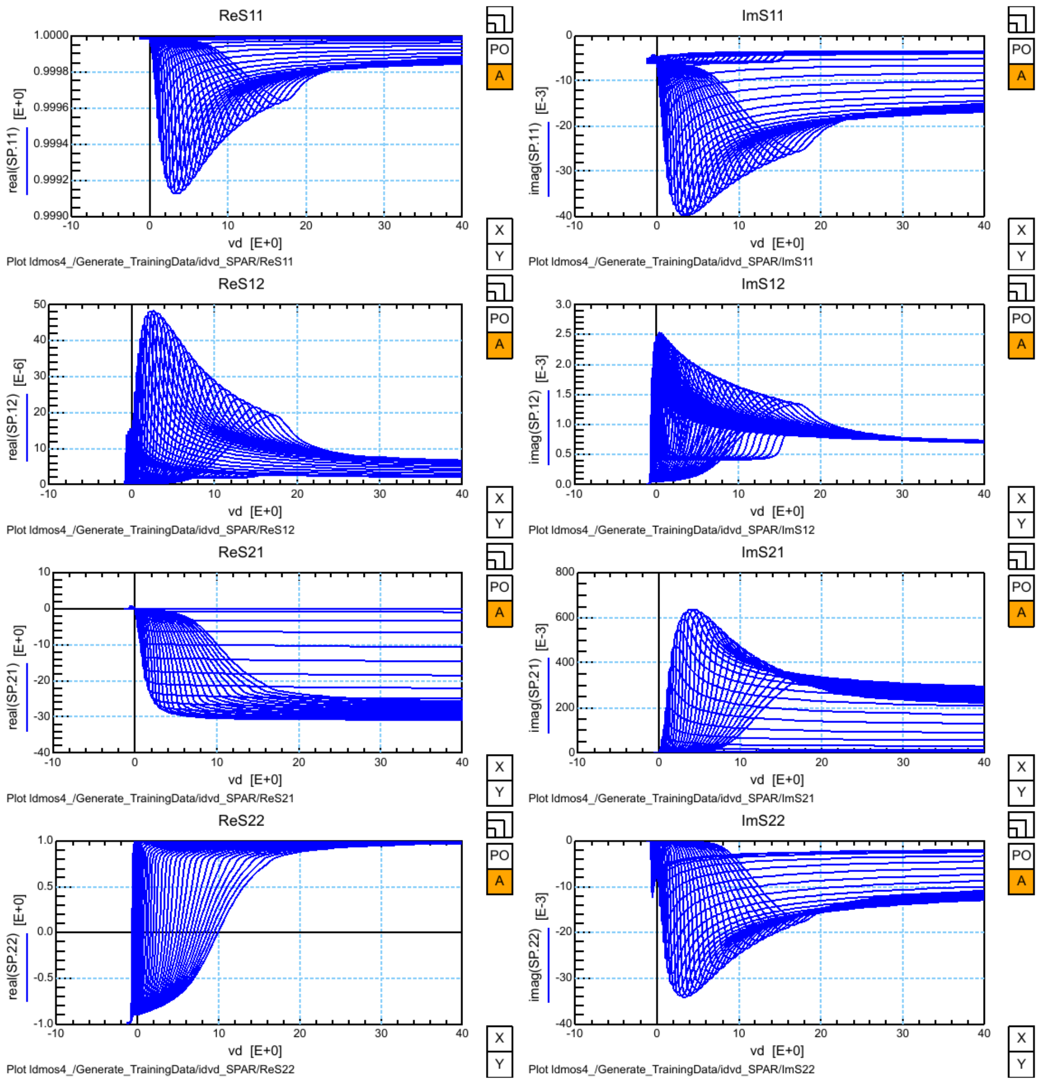
– ID(VGS=-7V, …,7V, step=**200mV**; VDS=-1V, …,40V, step=**200mV**)
– 206*71=14626 data points
– Approx. 25% of test data

For S-parameters test and training data same setup as for ID.

Training Data



AC Training Data

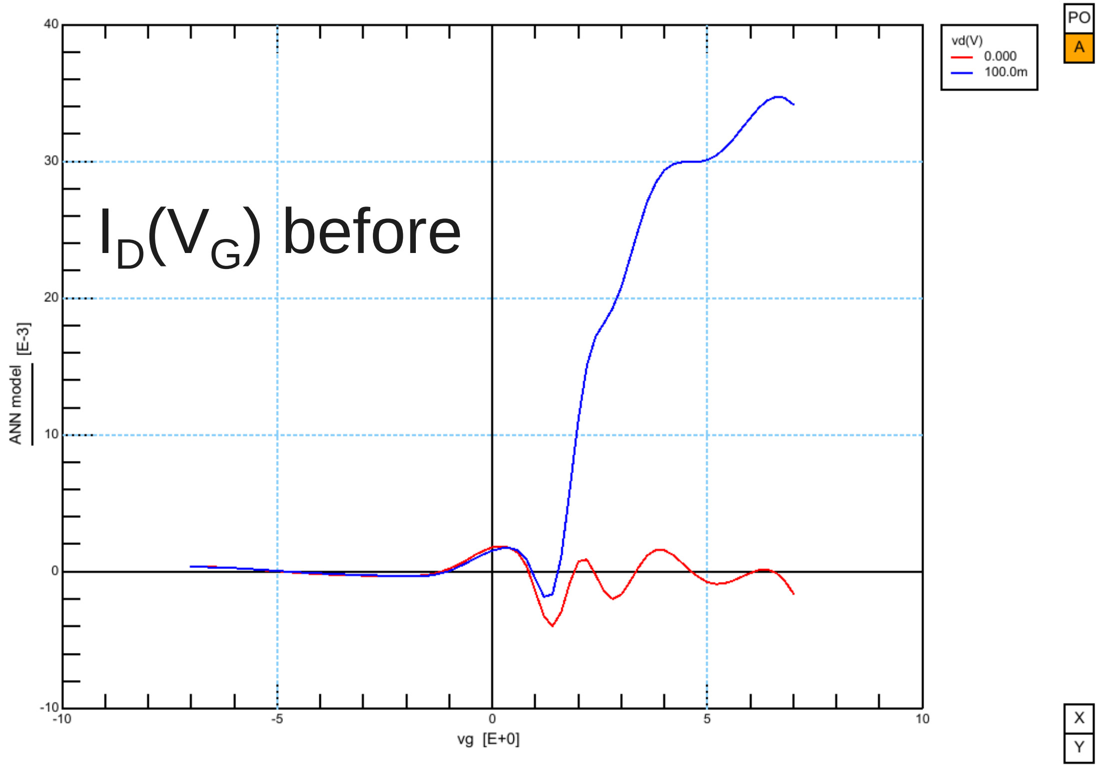


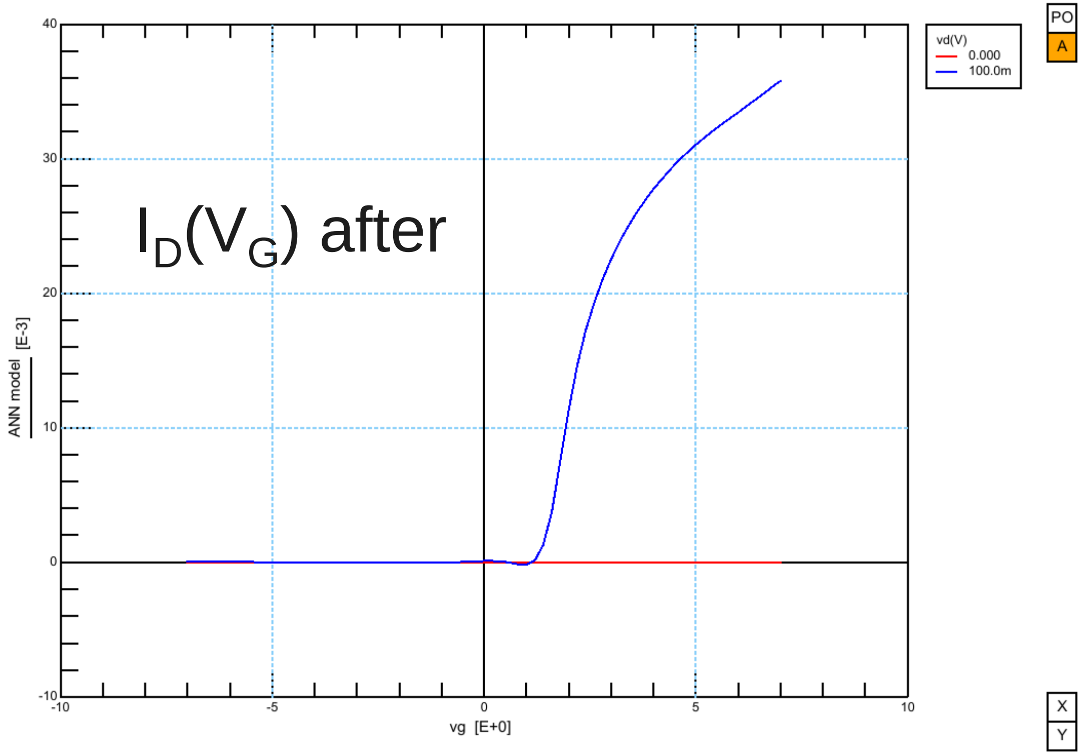
Problem 1

At V_D=0V the ANN model does not exactly calculate I_D=0A.

Solution

– ANN_Y=(I_D/V_D)



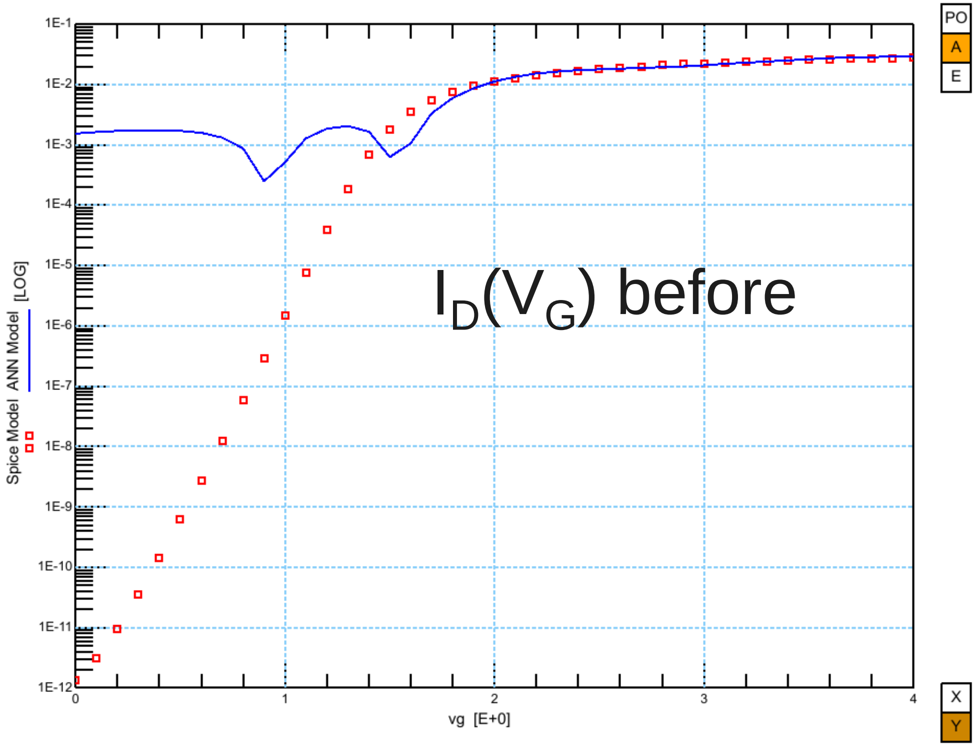


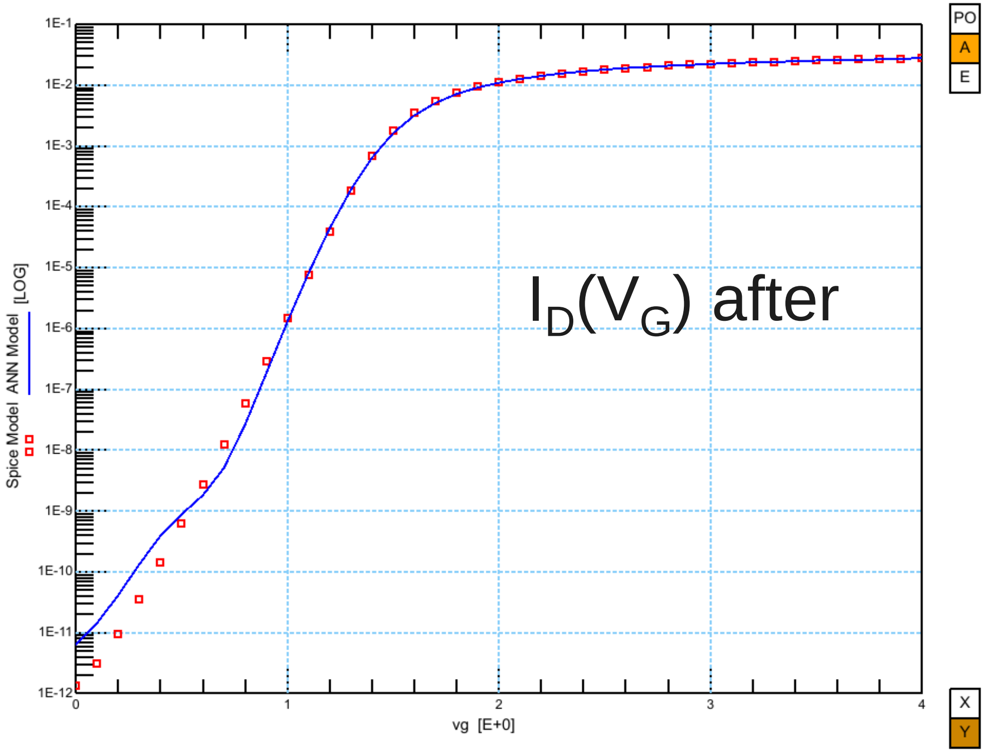
Problem 2

The ANN model is not accurate enough at small currents.

Solution

– ANN_Y=(I_D/V_D)**(1/5)



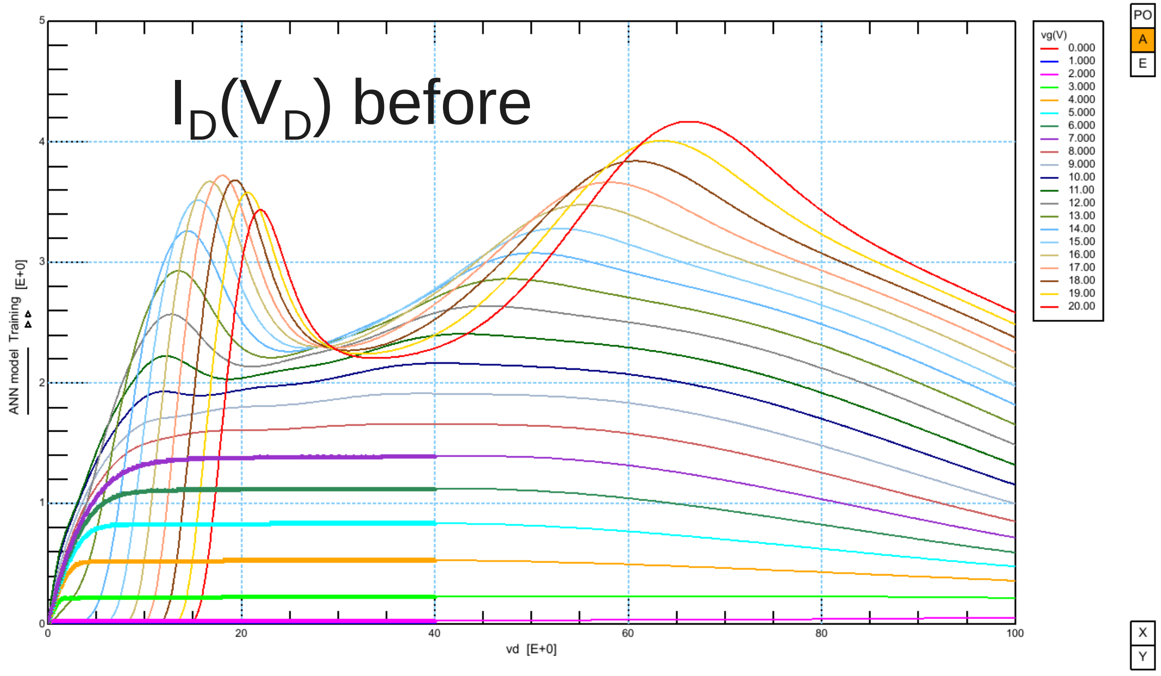


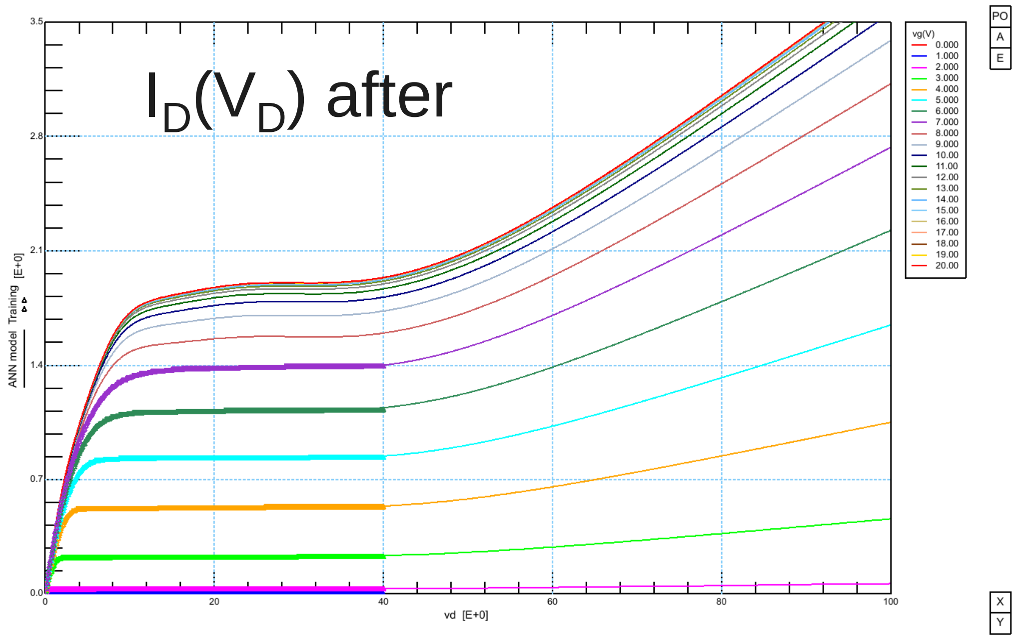
Problem 3

Outside the range of the training data characteristics show non-monotonic behavior

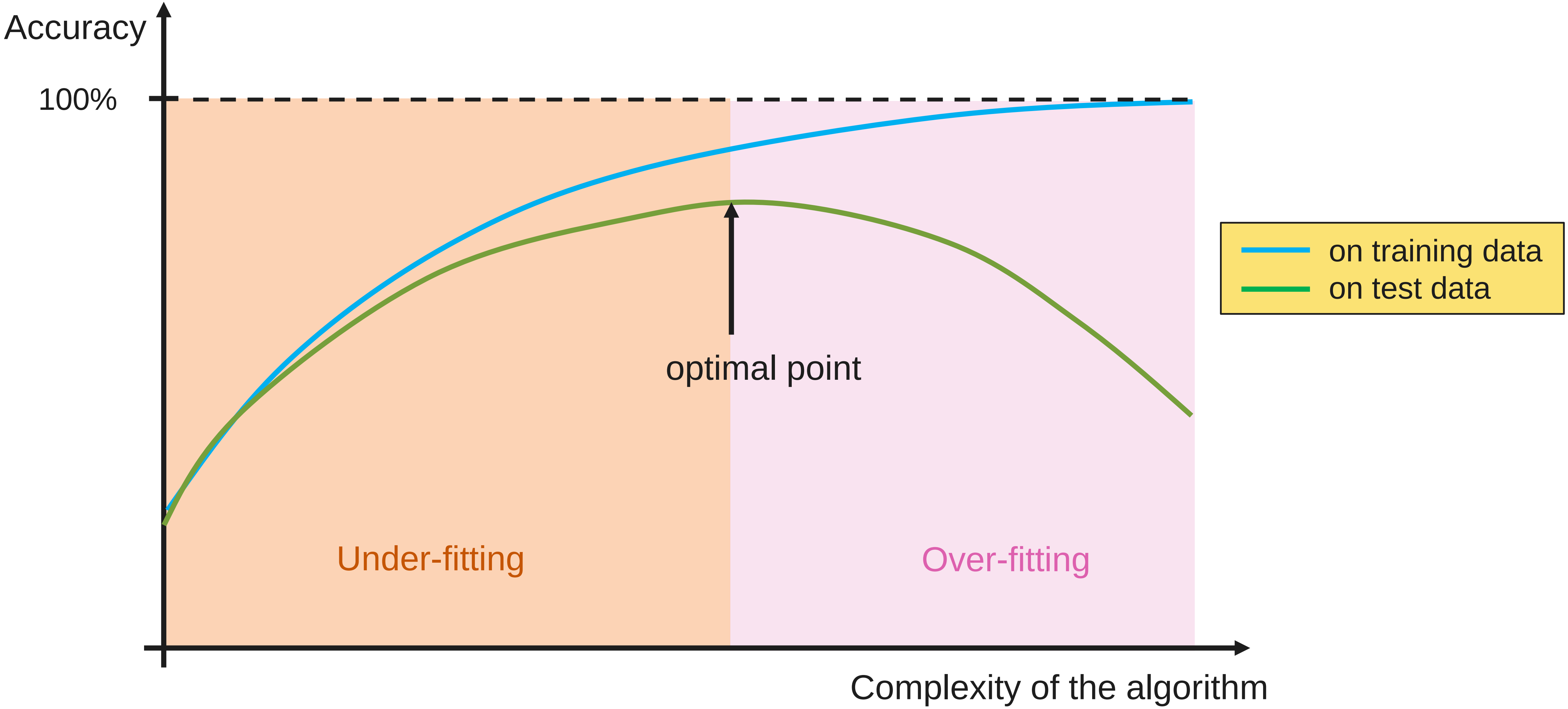
Solution

- ANN_X_0=tanh(2*(-1+2*(V_G+7)/14)) and
- ANN_X_1=tanh(2*V_D/40) for V_D>0V
- ANN_X_1=tanh(2*V_D/1)/40 for V_D<0V





Under-fitting and Over-fitting

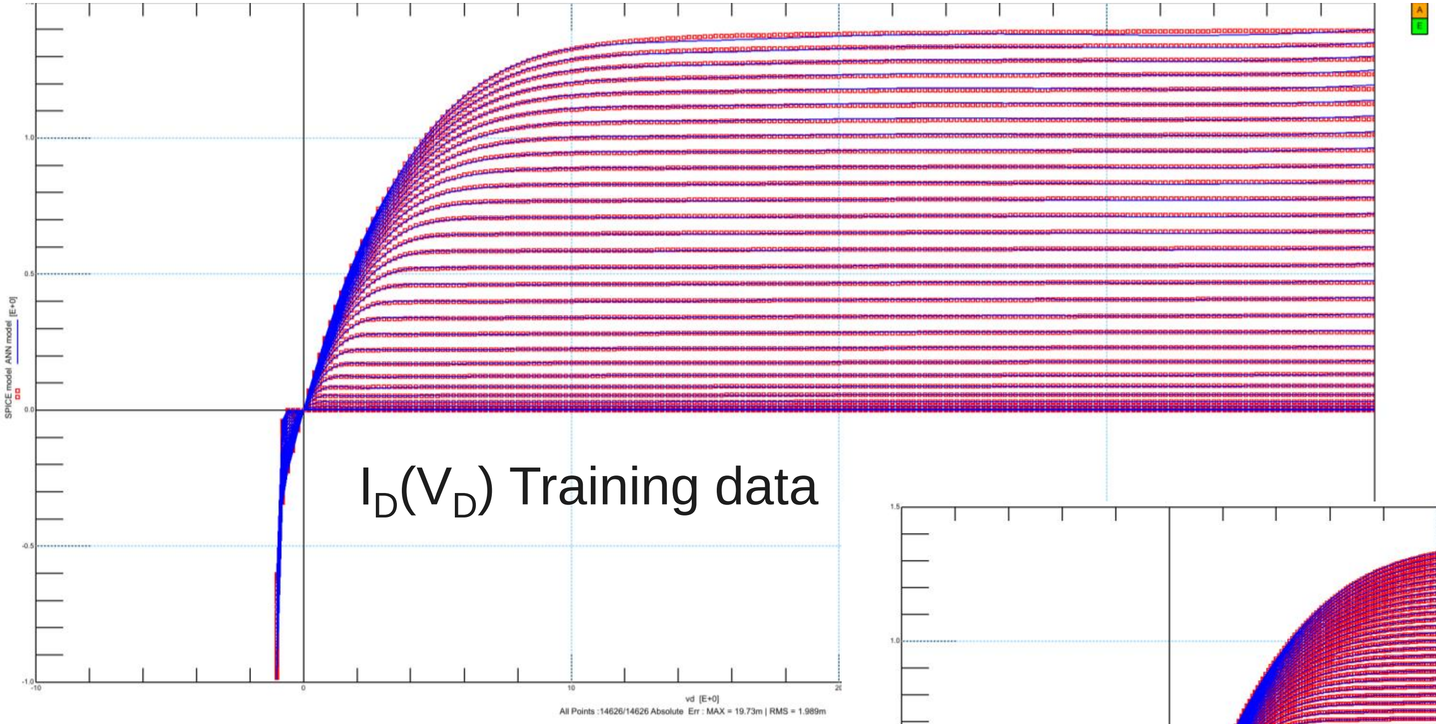


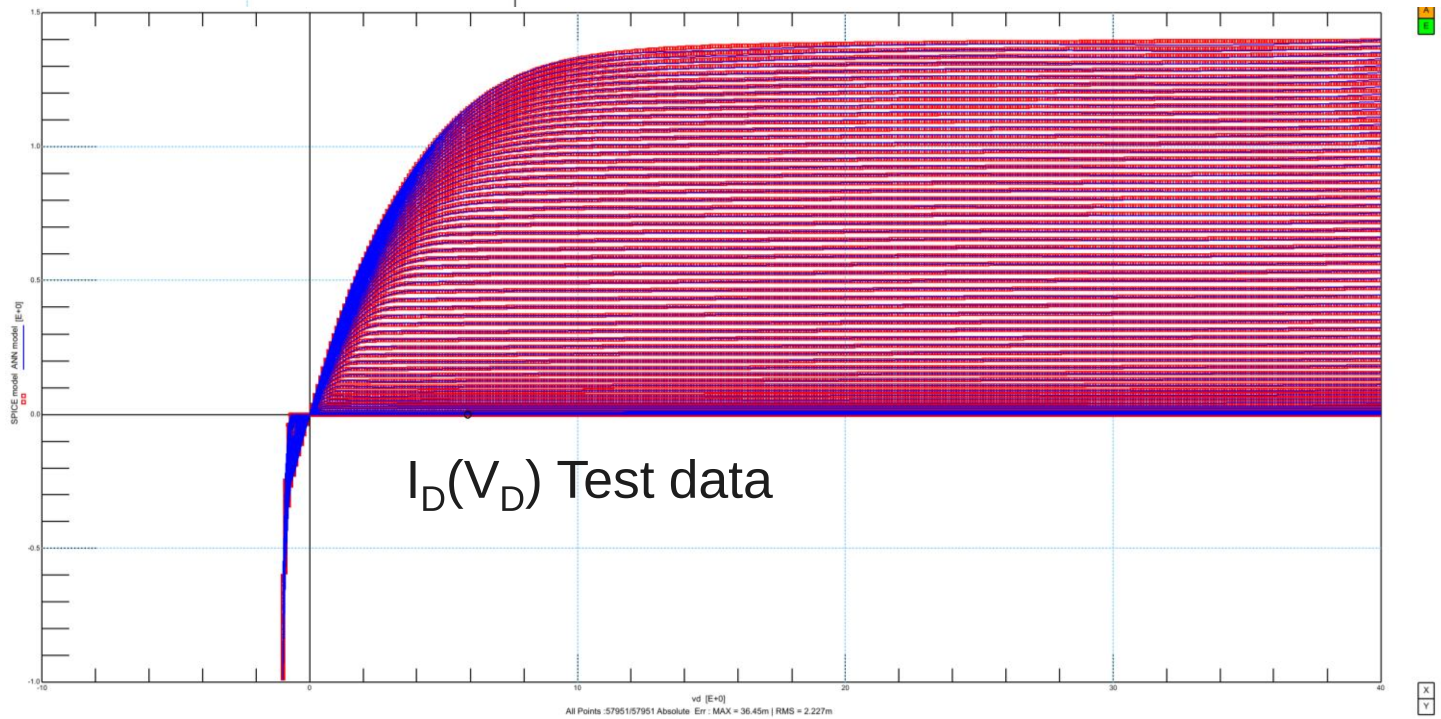
Optimal fitting

- 2 hidden layers and 14 neurons per layer was found as the optimum
- Hyperbolic Tangent better than RELU or Sigmoid

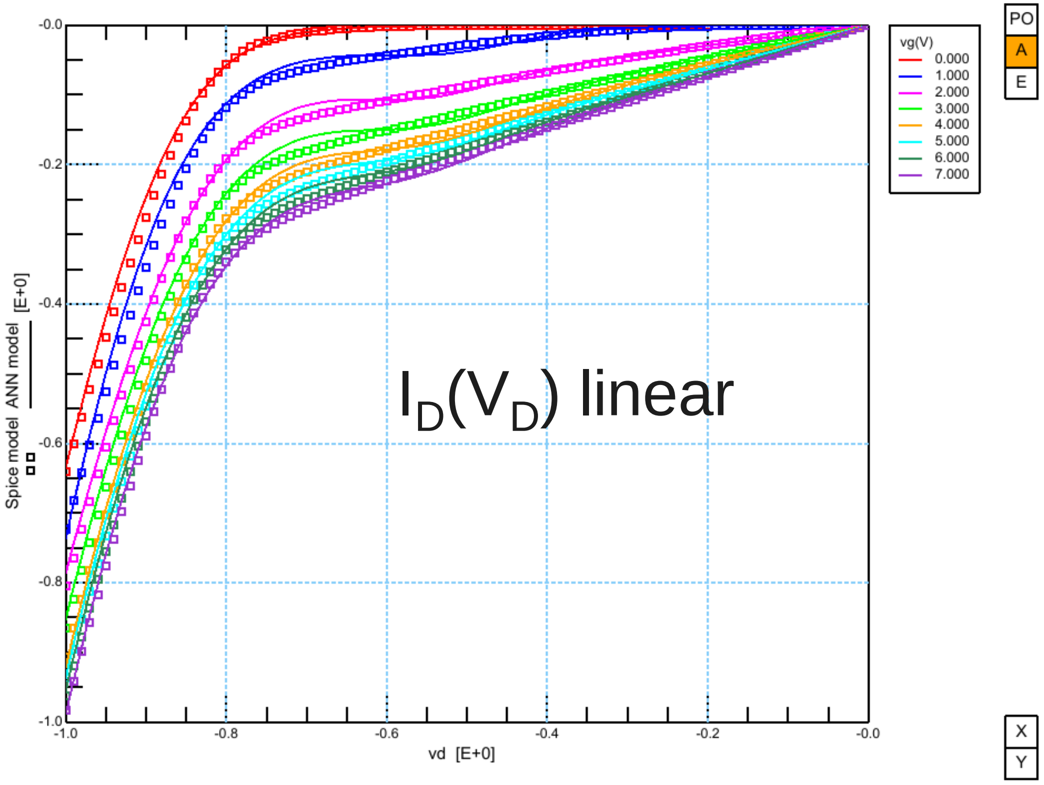
ANN Model		Training Data		Test Data	
Number of hidden layers	Number of Neurons per layer	Max. Error [mA]	RMS Error [mA]	Max. Error [mA]	RMS Error [mA]
2	9	58.72	8.409	76.93	8.175
2	10	66.42	9.111	66.42	8.8
2	11	51.06	4.883	51.45	5.024
2	12	28.72	1.833	84.24	3.19
2	13	26.93	2.743	88.54	3.52
2	14	15.91	1.349	39.48	2.316
2	15	15.96	1.34	85.29	3.588
2	16	12.09	1.252	66.67	2.384
2	17	25.03	2.139	45.18	2.608
3	6	44.79	4.15	46.29	4.179
3	7	24.67	2.506	63.23	3.173
3	8	23.78	2.767	147.2	6.294
3	9	13.21	1.133	96.04	3.586

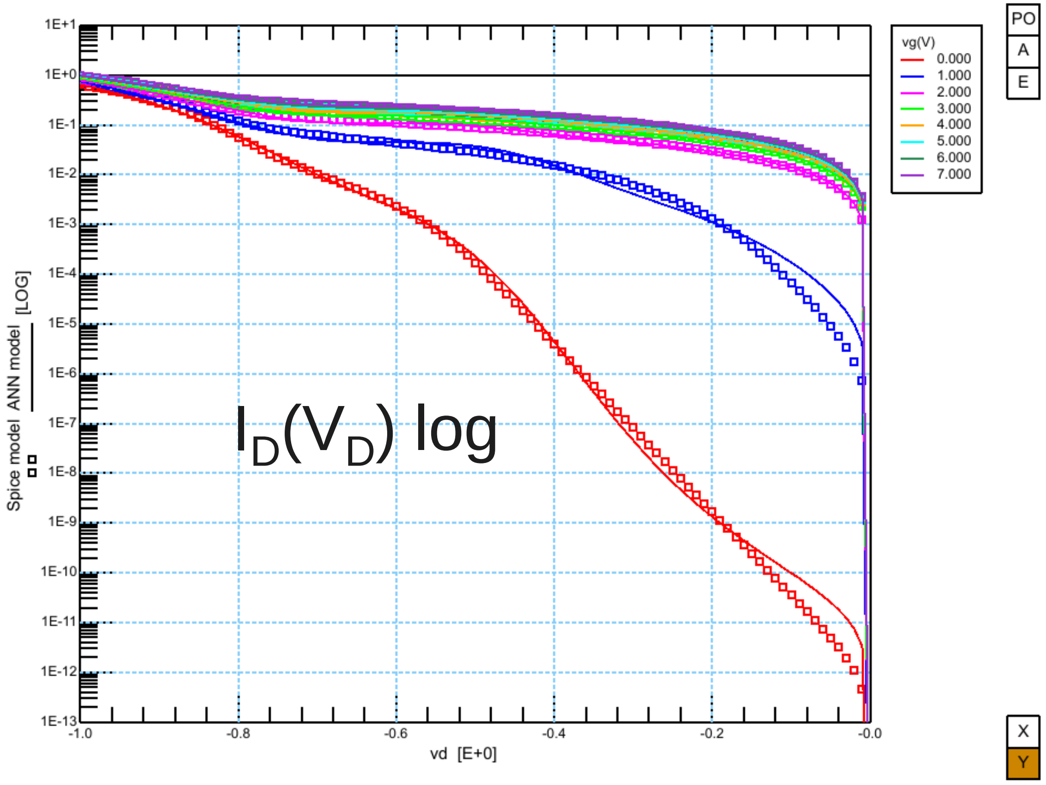
Training result with 2 hidden layers / 14 nodes per layer





Training result with 2 hidden layers / 14 nodes per layer, diode



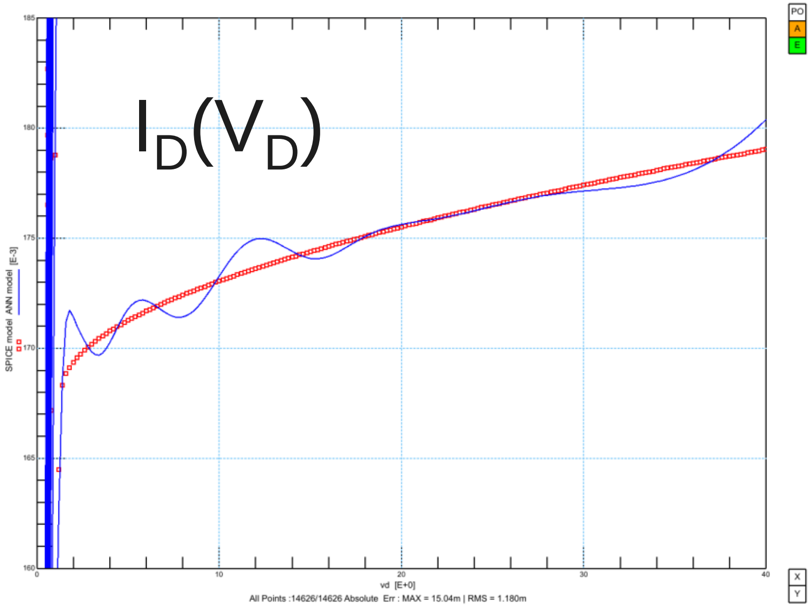


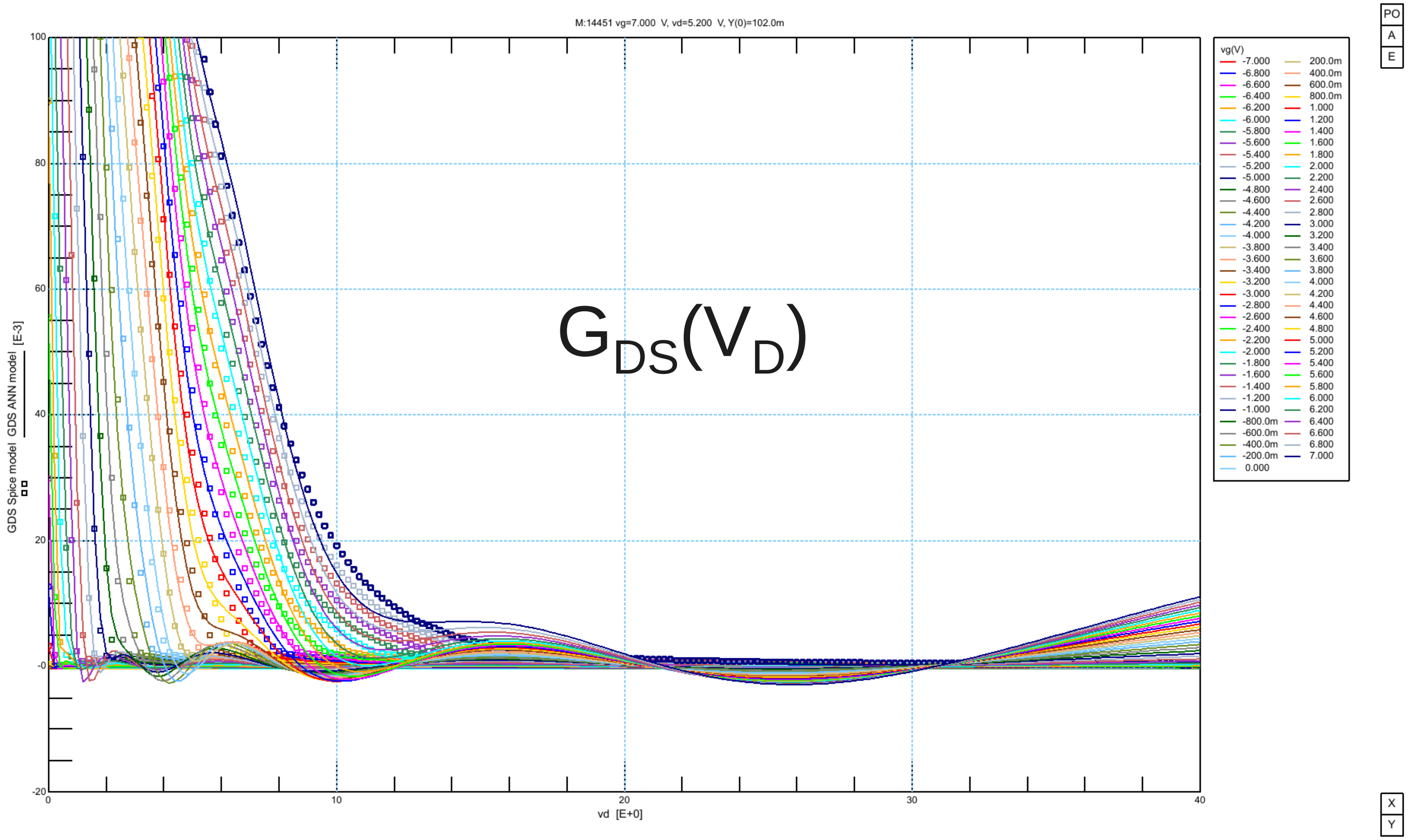
Problem 4

Output currents are wave-like, negative differential output resistances occur

Solution

– ???





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Summary

- Modeling an 40V-LDMOS with an ANN Network has been tested
- Special Scaling of Training Input and Output data is necessary to obtain a good Model
- The Problem of Negative Differential Resistances is not solved yet

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