AMRITA VISHWA VIDYAPEETHAM

Modeling and Predicting Bacterial Growth Using an Analog Circuit and RNN

Introduction to NN, CNN and GNN (24AIM113)
Analog system design (24AIM114)

RAGUL U. - CB.AI.U4AIM24036
RAMKUMAR R. - CB.AI.U4AIM24033
SHWETHA P. - CB.AI.U4AIM24042
PRAGALYA M. - CB.AI.U4AIM24032

Objective

- To use analog computing to simulate bacterial growth under different conditions and then Collect the real-time data for analysis.
- To train an RNN-based model to predict bacterial growth trends
- To study how changing the nutrient concentration affects bacterial growth. Use DL to generalize patterns beyond experimental conditions

Progress so far :

- Generated out own data which mimics the circuits output.
- Created the working simulation of the analog circuit, which outputs the approximate bacterial growth values
- Built an LSTM which could predict the variation in growth for different nutrient levels.
- Trained the same data with different Models, and choose the one that gave the best accuracy.

Mathematical Model of Bacterial Growth

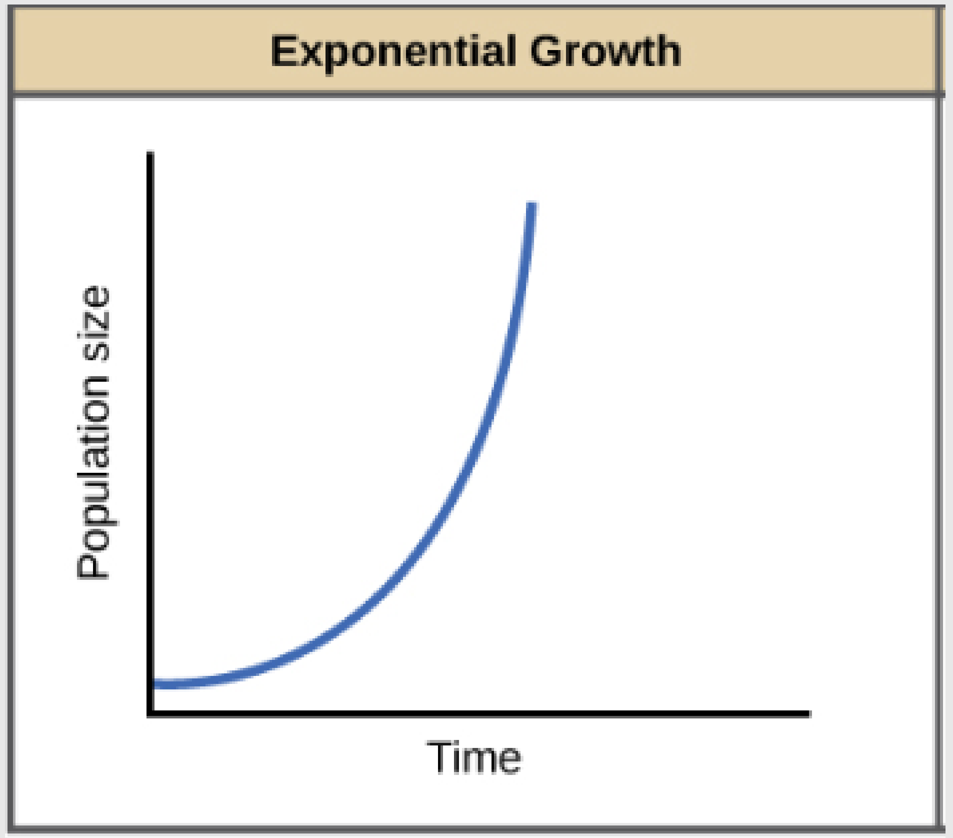
Population at time t

Growth Rate

$$N(t) = N_0 e^{rt}$$

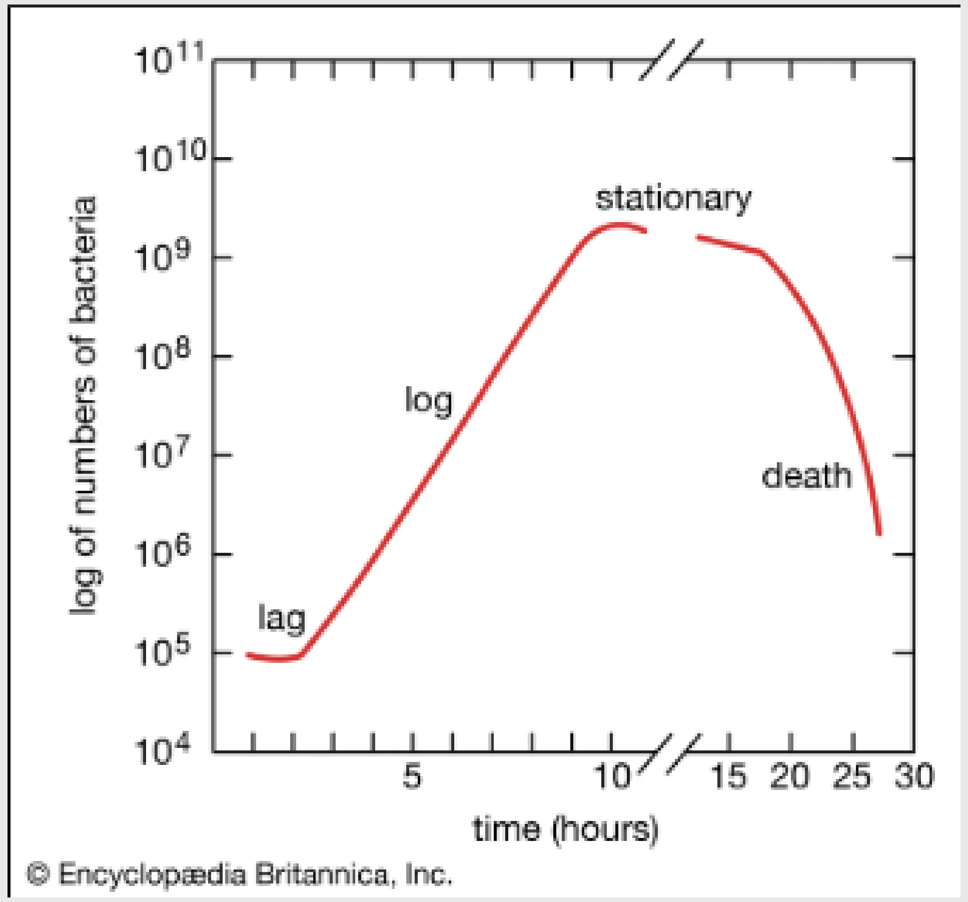
Time

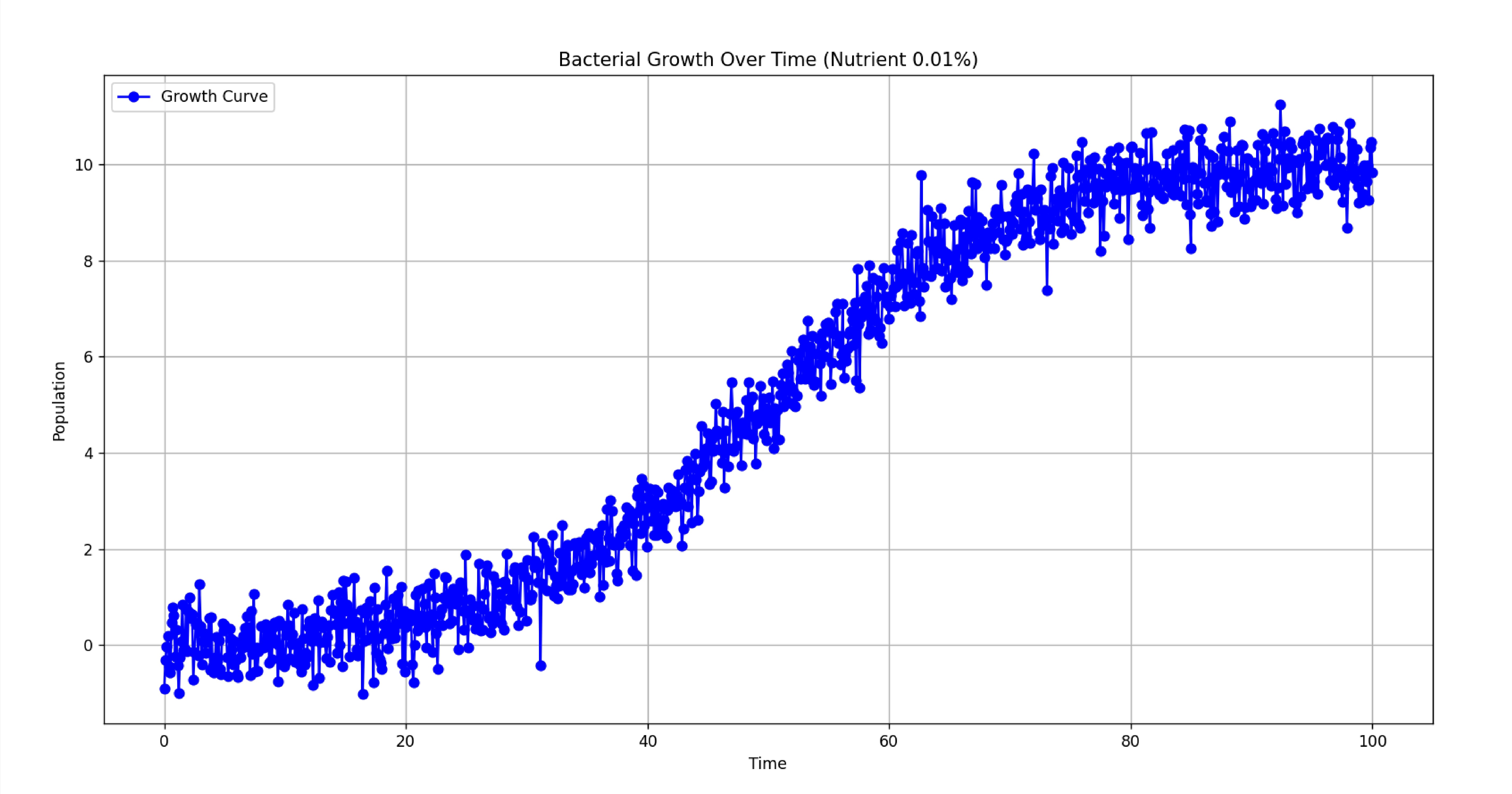
Initial Population

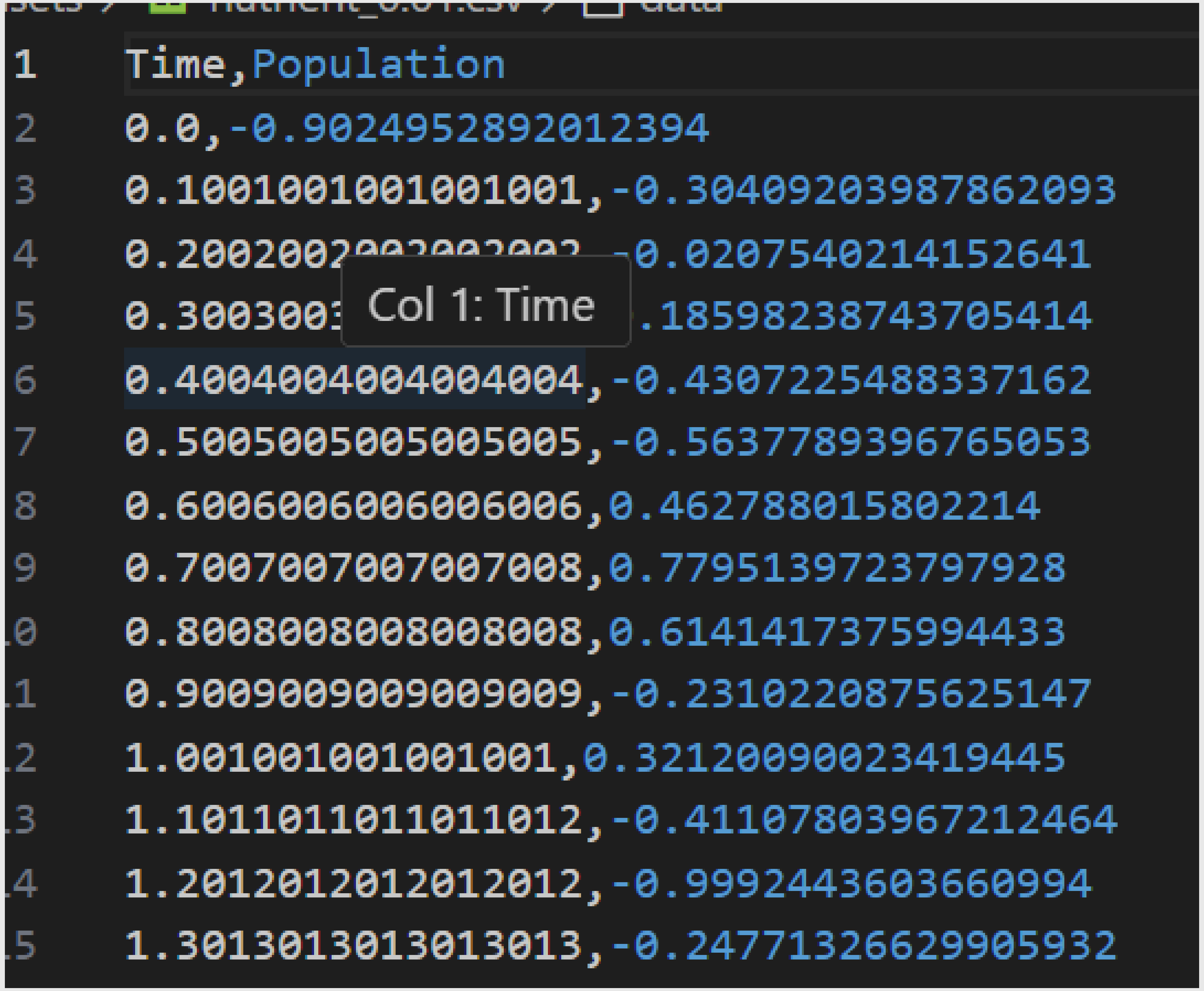


Carrying Capacity

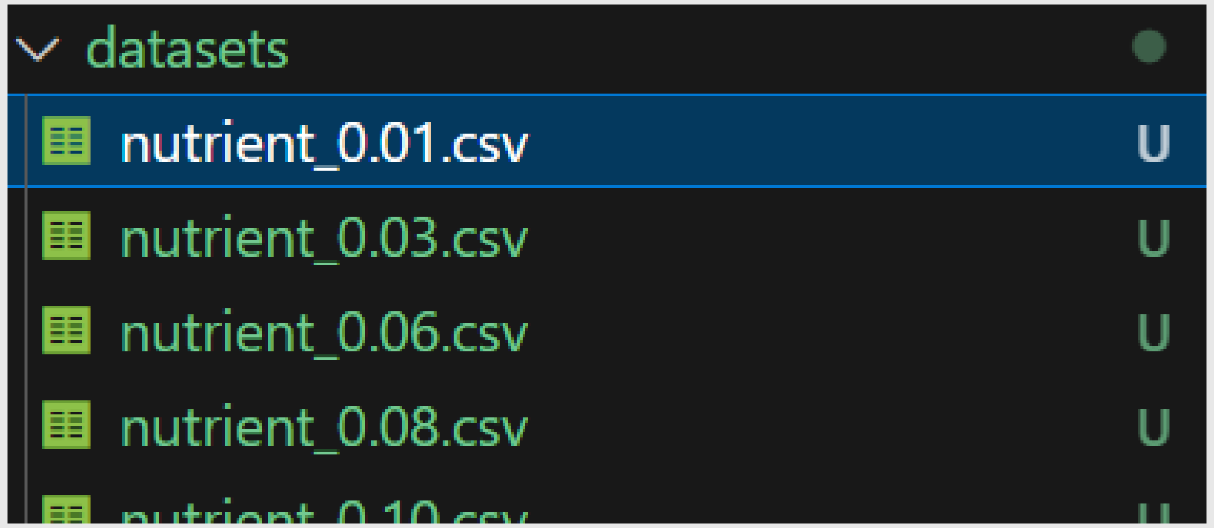
$$N(t) = \frac{N_0 K}{N_0 + (K - N_0)e^{-rt}}$$




Bacterial Growth Over Time (Nutrient 0.01%)
Growth Curve
Population
Time
0
2
4
6
8
10
0
20
40
60
80
100



Time,Population
0.0,-0.9024952892012394
0.1001001001001001,-0.30409203987862093
0.2002002 -0.0207540214152641
0.3003003 .18598238743705414
Col 1: Time
0.4004004004004004,-0.4307225488337162
0.5005005005005005,-0.5637789396765053
0.6006006006006006,0.462788015802214
0.7007007007007008,0.7795139723797928
0.8008008008008008,0.614141737599443
0.9009009009009009,-0.2310220875625147
1.001001001001001,0.3212009002341944
1.1011011011011012,-0.41107803967212464
1.2012012012012012,-0.999244360366099
1.3013013013013013,-0.24771326629905932



datasets
nutrient_0.01.csv U
nutrient_0.03.csv U
nutrient_0.06.csv U
nutrient_0.08.csv U

Hardware

ADALM2000

Function generator,
oscilloscope, power supply,
and data acquisition system

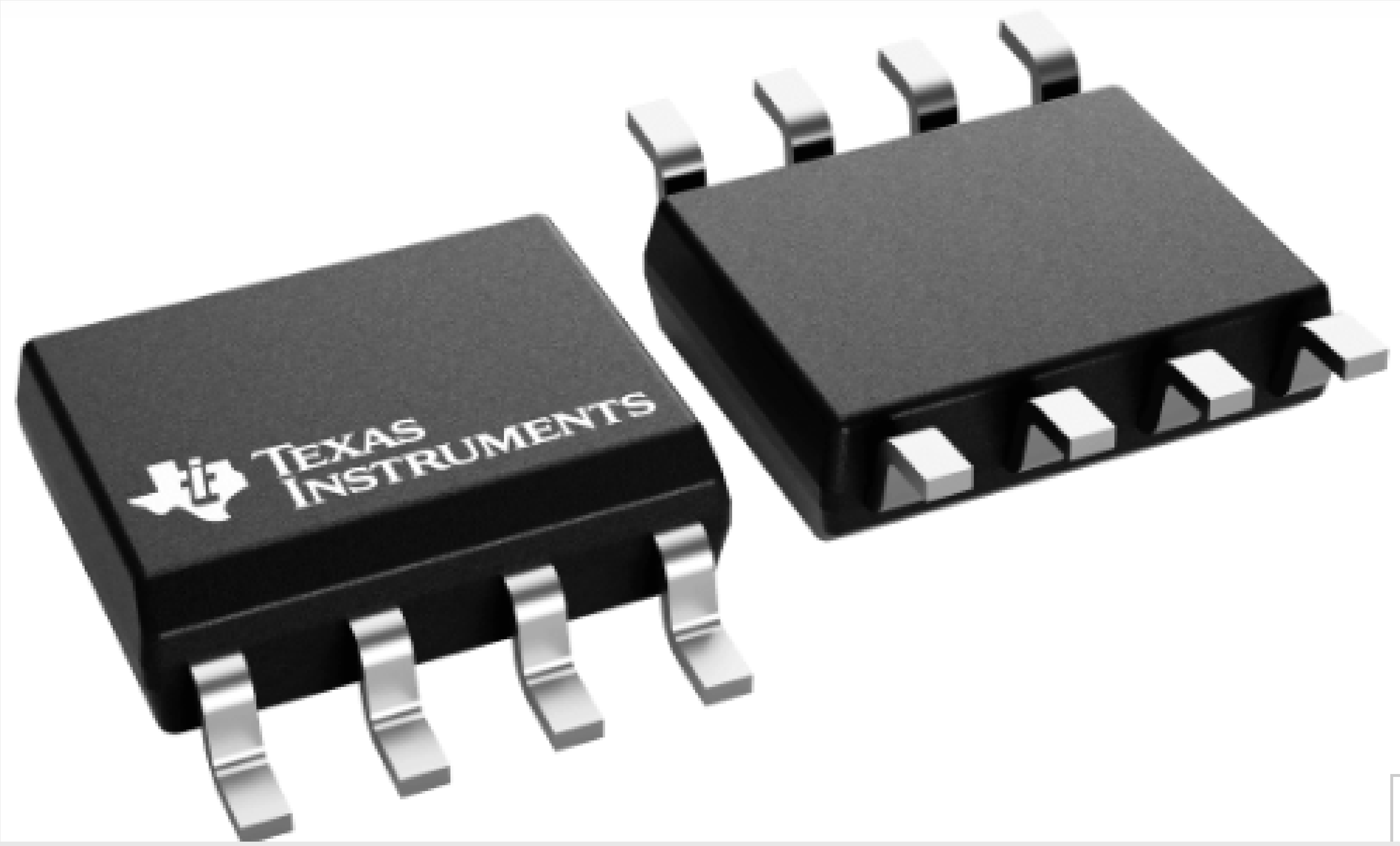
Arduino UNO

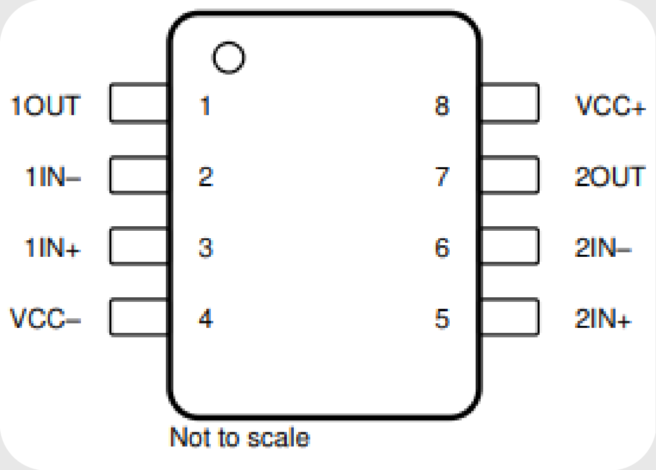
Standalone data logging,
Control external parameters,
Additional analog inputs

TL081

1 Features

- High slew rate: 20V/µs (TL08xH, typ)
- Low offset voltage: 1mV (TL08xH, typ)
- Low offset voltage drift: 2 µV/°C
- Low power consumption: 940µA/ch (TL08xH, typ)
- Wide common-mode and differential voltage ranges
  - Common-mode input voltage range includes V_{CC+}
- Low input bias and offset currents
- Low noise: $V_n = 18nV/\sqrt{Hz}$ (typ) at f = 1kHz
- Output short-circuit protection
- Low total harmonic distortion: 0.003% (typ)
- Wide supply voltage: ±2.25V to ±20V, 4.5V to 40V





AMRITA VISHWA VIDYAPEETHAM

Time Constant for Bacterial Growth Simulation

- For bacterial growth, the model should have a relatively slow rise in signal over time to reflect the realistic doubling time of bacterial growth.
- The doubling time for bacteria like E. coli is typically around 20 to 30 minutes in ideal conditions.

$$\tau = R \cdot C$$

If $(R = 220k\Omega) and (C = 100\mu F)$

$$\tau = 220,000 \times 100 \times 10^{-6} = 22 sec$$

Analog Computation for Growth Simulation

$$\frac{dN}{dt} = rN$$

Where :

- N(t) = bacterial population
- r = growth rate

Op-Amp Integrator :

Computes N(t) from dN/dt.

Resistor (R) & Capacitor (C) :

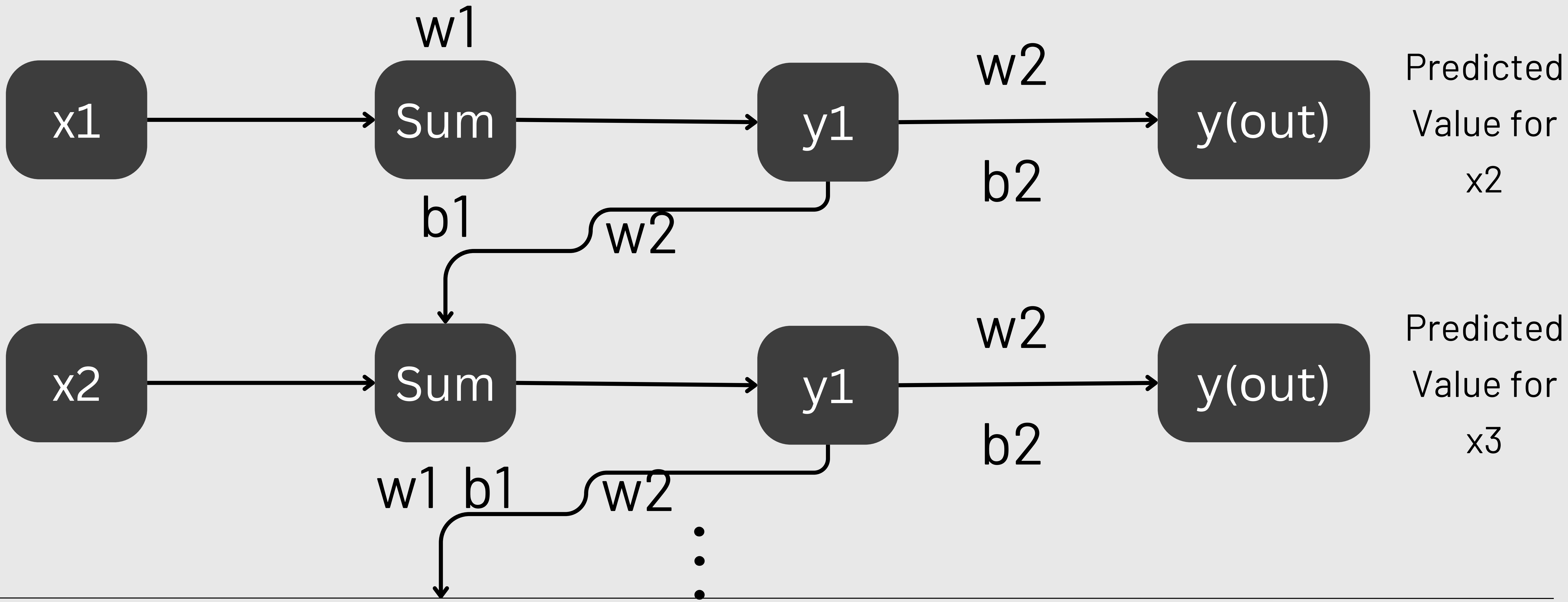
Define time constant (τ=RC).

Output Signal :

Exponential voltage curve simulating bacterial growth

Recurrent Neural Network (RNN) Model

- Designed to process sequential data by maintaining memory of past inputs.



Exploring Various other Models :

GRU (Gated Recurrent Unit) :

- Uses gating mechanisms to control the flow of information without needing a separate cell state like LSTM
- GRU has two main gates:

    Update Gate – Controls how much past information to carry forward.

    Reset Gate – Controls how much of the past information to forget.

$R^2 = 0.9795$

Accuracy = 97.95%

Exploring Various other Models :

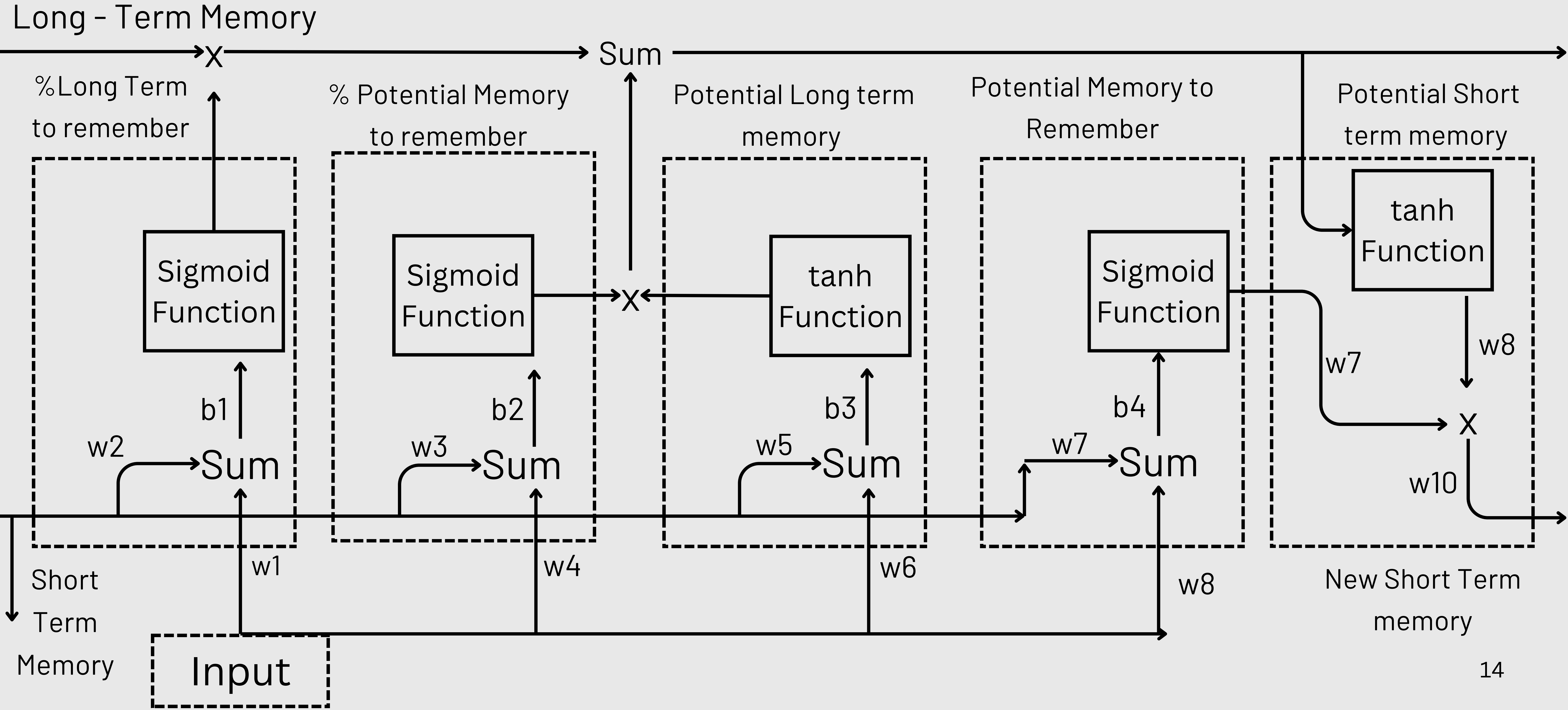
1D CNN (1-Dimensional Convolutional Neural Network) :

- A filter (kernel) slides over the input data (sequence) to capture patterns.
- Each filter extracts local features such as trends, spikes, or patterns in the sequence.
- Mostly used for Time-series data

$R^2 = 0.9802$

Accuracy = 98.02%

Long short term memory (LSTM)



- LSTM Layer - 50 Units Used
- LSTM gives 3 outputs :
    - Hidden State - Represents short-term memory.
    - Cell State - Represents long-term memory.
    - Final Output -The hidden state of the last time step.
- 3 Outputs will be sent to a Single layer network to output the final prediction
- Linear Activation in the Last Layer
- Dropout Layer : A Dropout layer randomly drops (disables) a fraction of neurons during training

Model Comparison

LSTM : 98.19%

1D-CNN : 98.02%

GRU : 97.90%

LSTM vs 1D-CNN : -0.17%

LSTM vs GRU : -0.29

In all various runs, LSTM gave the best accuracy

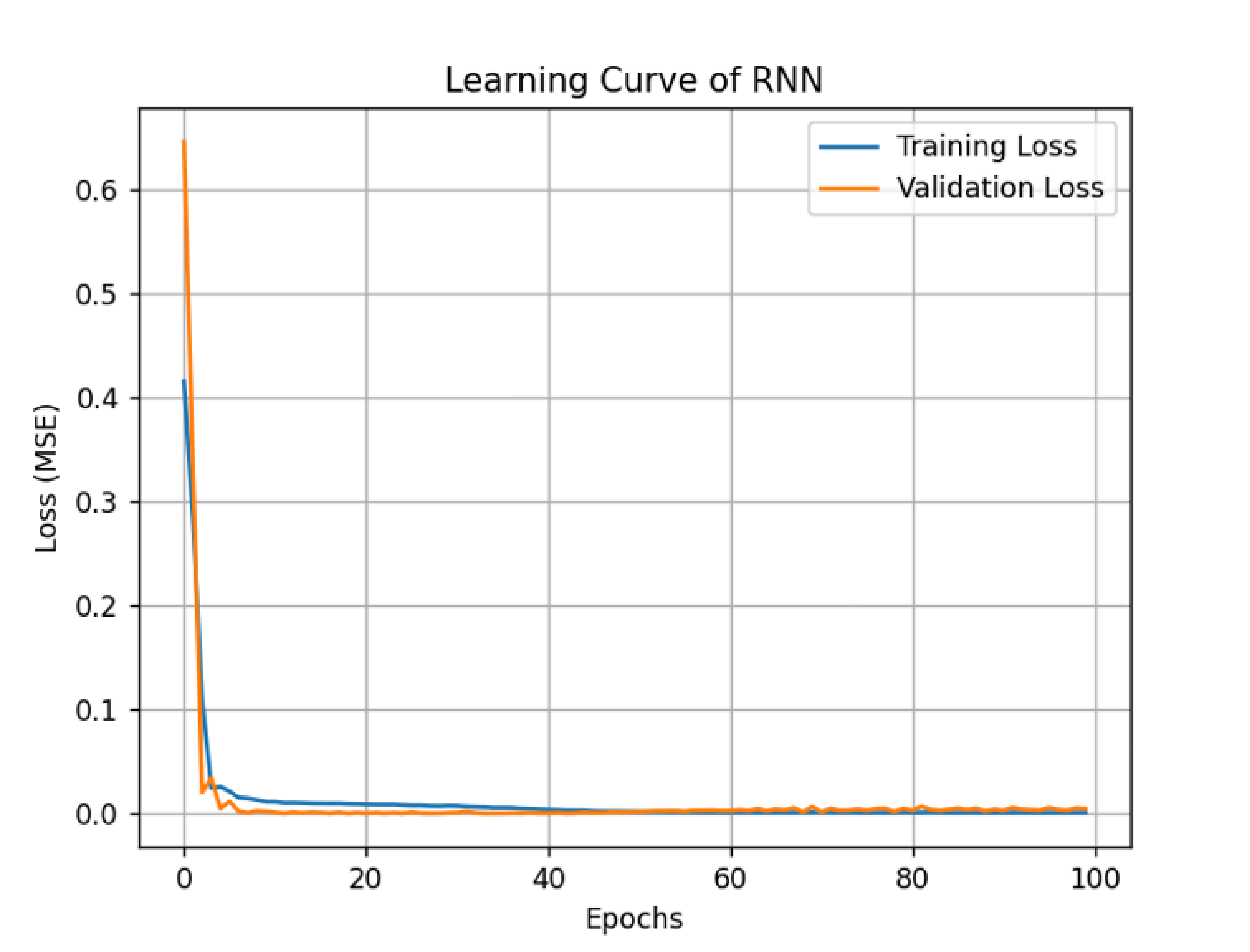
Software for RNN-Based Growth Prediction

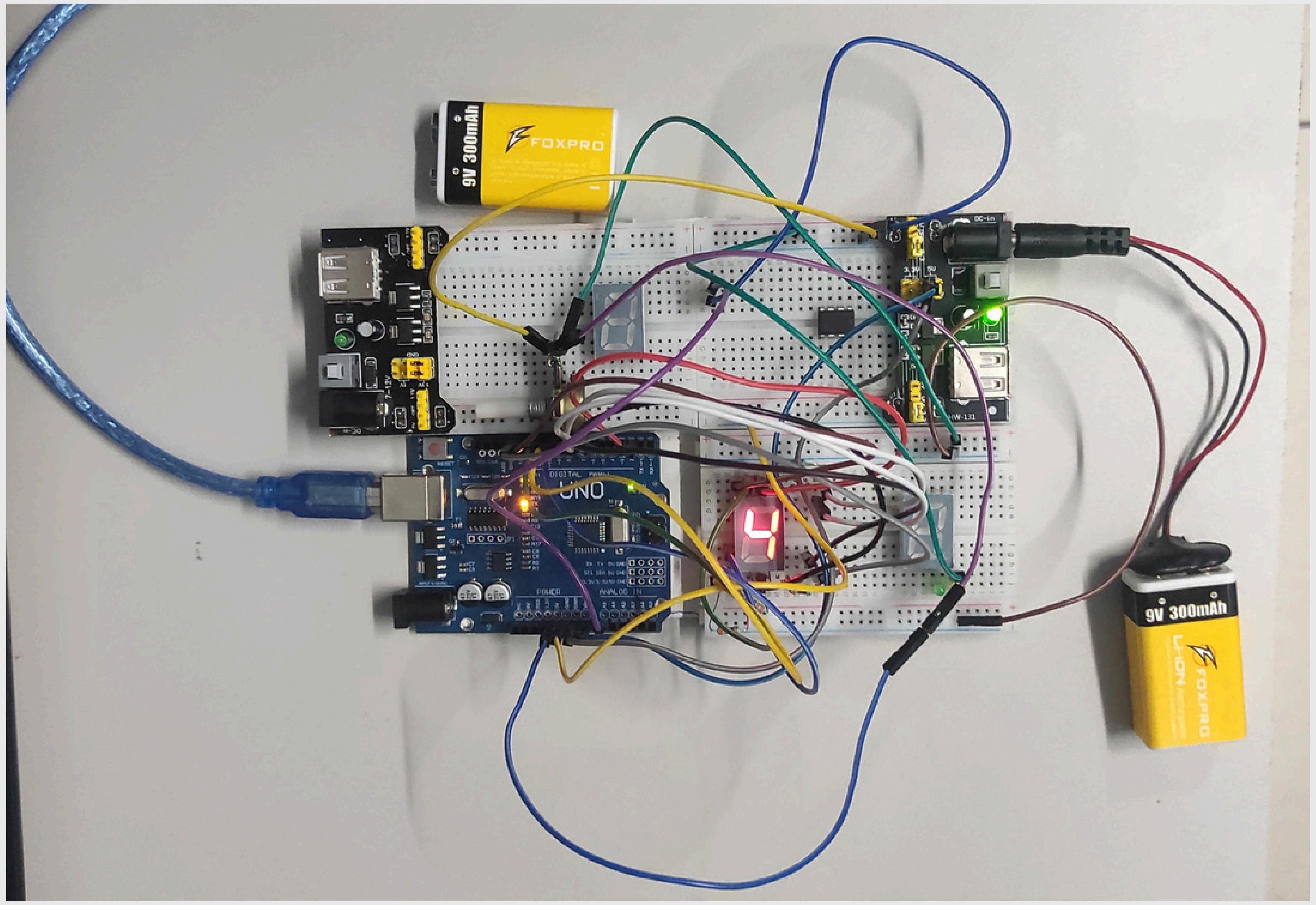
- Main Programming Language : Python
- Machine Learning & Deep Learning Libraries
    - TensorFlow / PyTorch
    - Scikit-Learn
    - Keras
- Data Processing & Analysis
    - NumPy & Pandas
    - Matplotlib & Seaborn

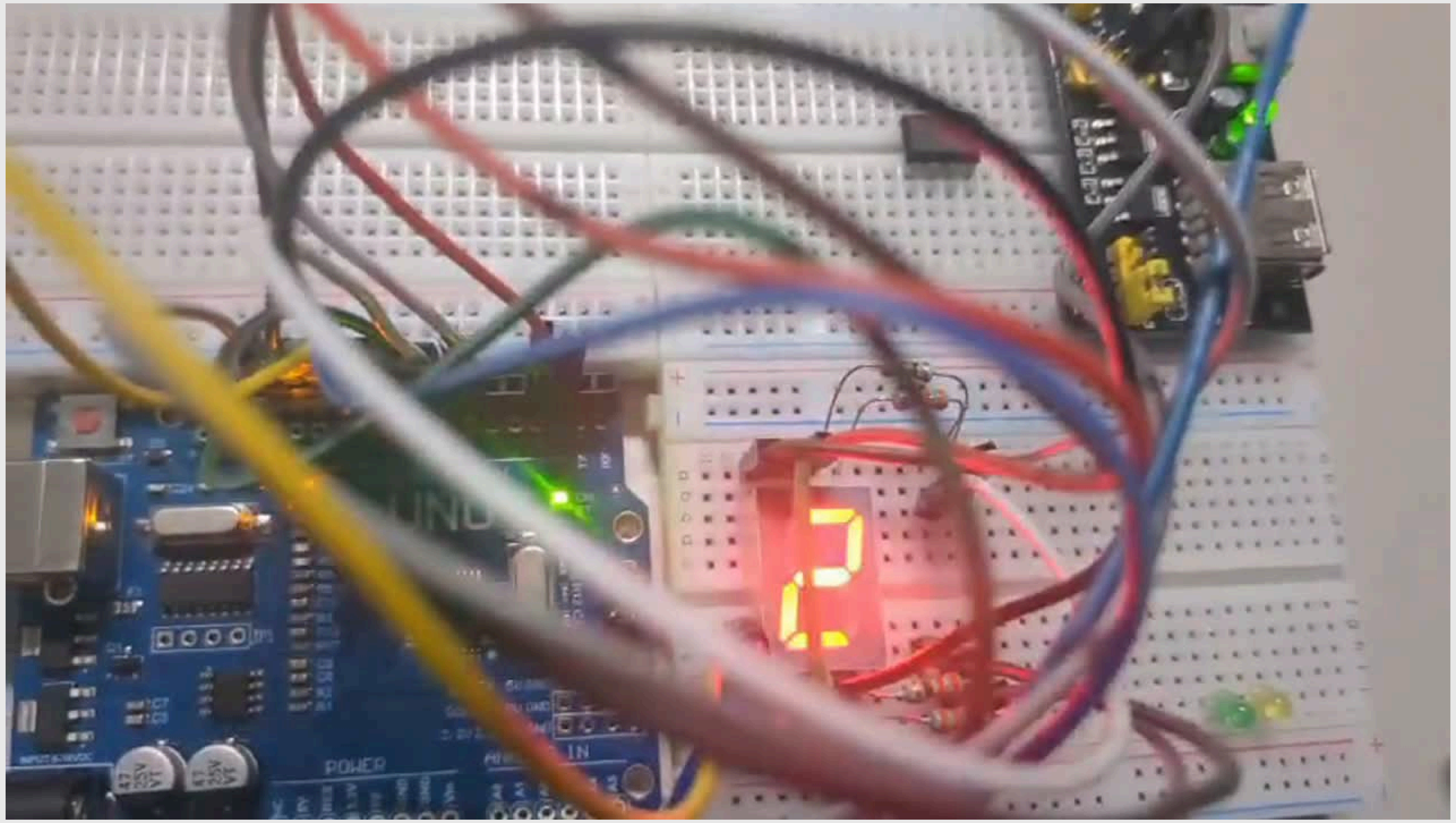
Parameters

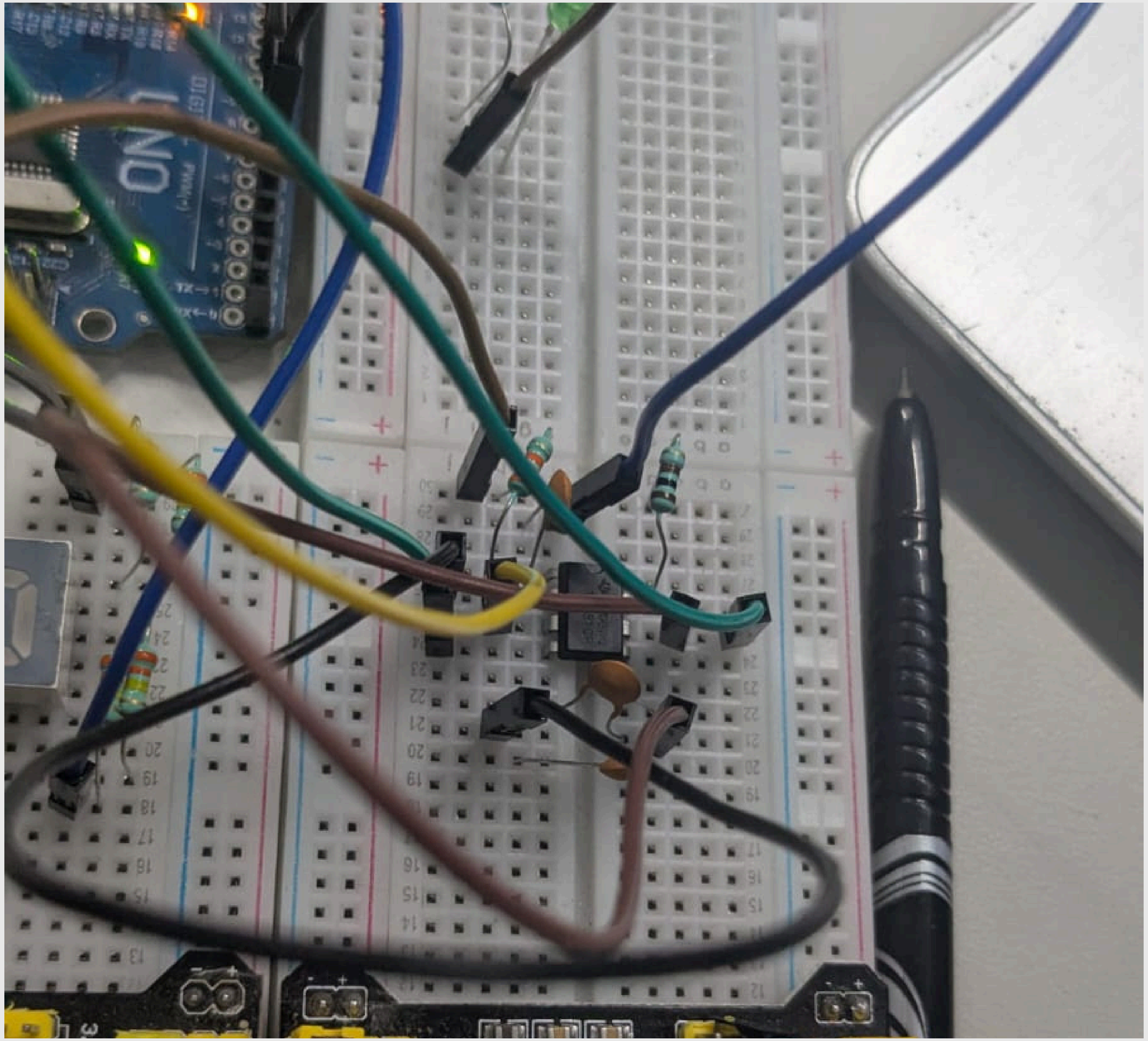
- Learning Rate : 0.001
- Loss Function : Mean Squared Error
- Batch Size : 32 - Good for balance between speed and stability.
- Epoch : 50 - 200 : Higher epochs allow for better learning but there is a risk of overfitting.
- Optimizer : Adam - Adaptive learning rate optimizer. Works well for time-series tasks

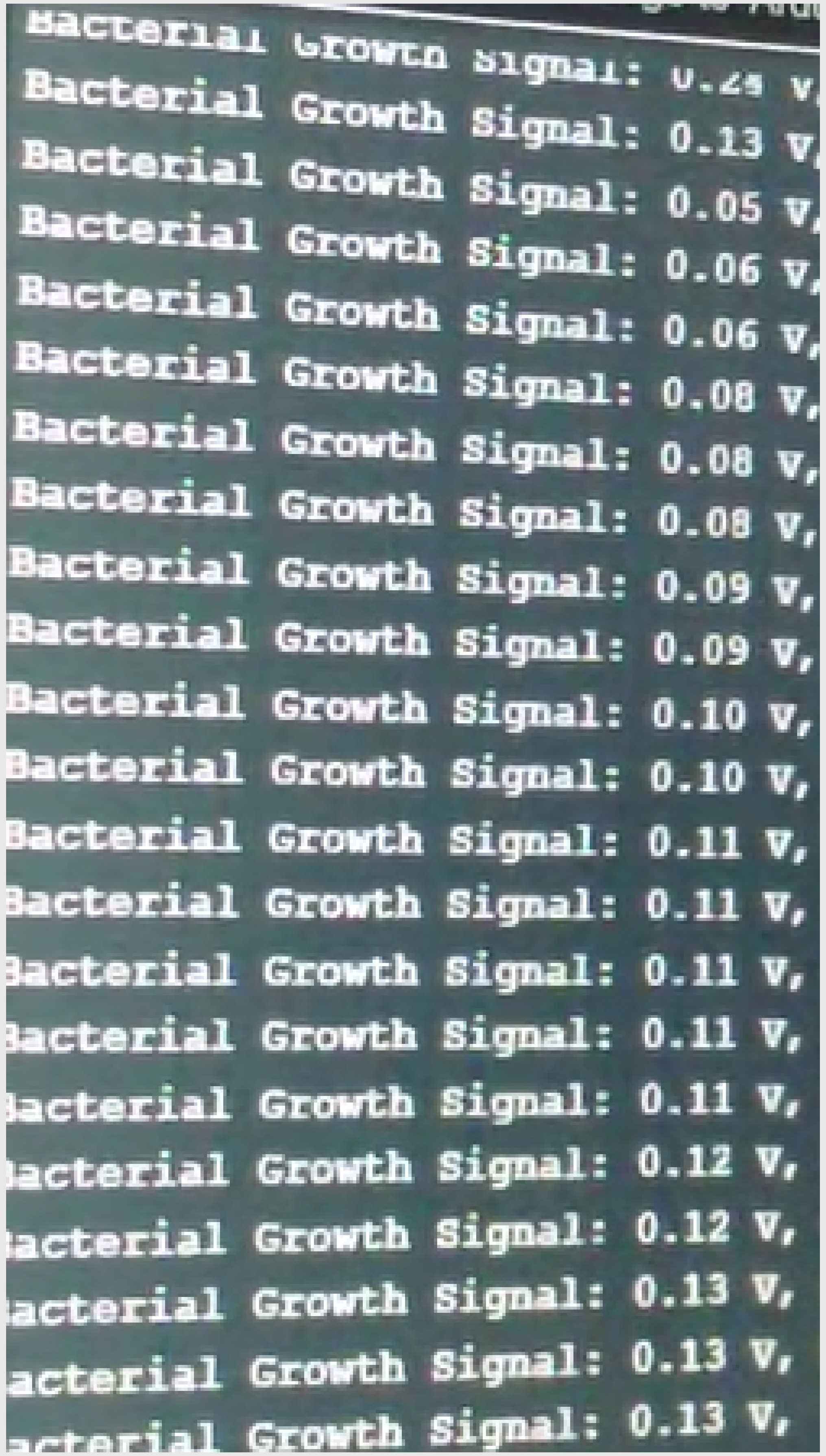
Learning Curve

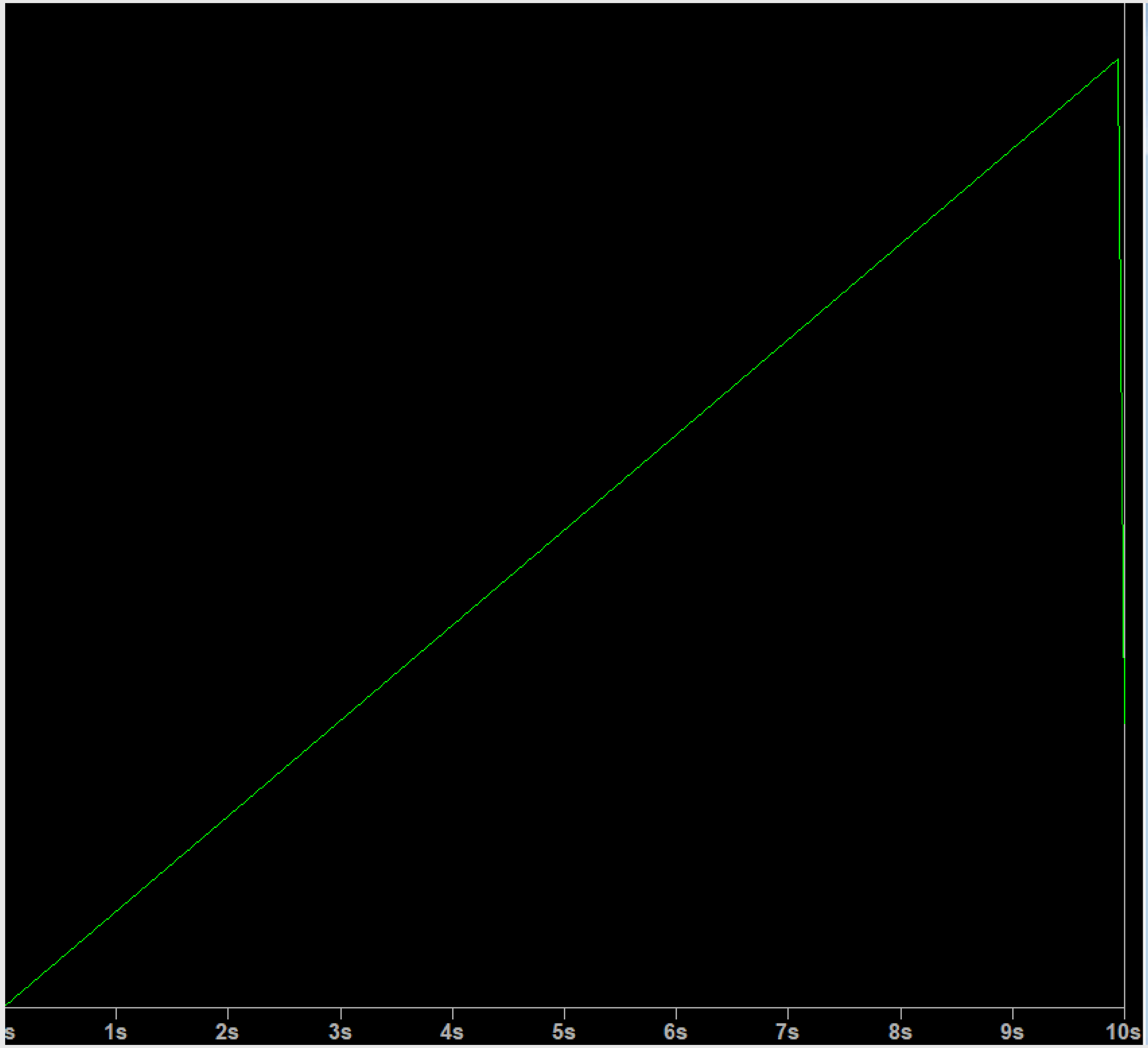


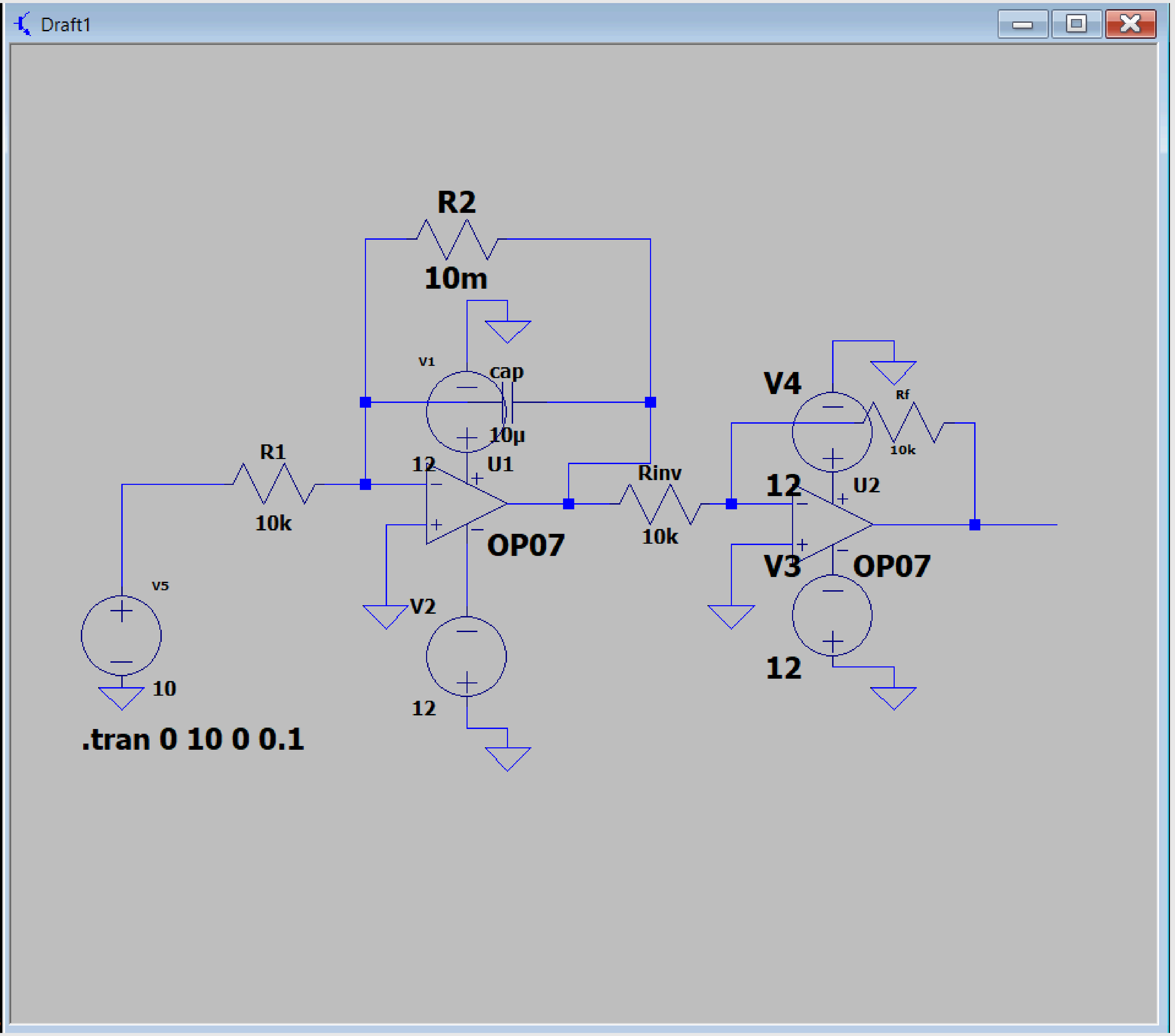

9V 300mAh
FOXPRO
9V 300mAh
FOXPRO






Bacterial Growth Signal: 0.13 V,
Bacterial Growth Signal: 0.05 V,
Bacterial Growth Signal: 0.06 V,
Bacterial Growth Signal: 0.06 V,
Bacterial Growth Signal: 0.08 V,
Bacterial Growth Signal: 0.08 V,
Bacterial Growth Signal: 0.08 V,
Bacterial Growth Signal: 0.09 V,
Bacterial Growth Signal: 0.09 V,
Bacterial Growth Signal: 0.10 V,
Bacterial Growth Signal: 0.10 V,
Bacterial Growth Signal: 0.11 V,
Bacterial Growth Signal: 0.11 V,
acterial Growth Signal: 0.11 V,
acterial Growth Signal: 0.11 V,
acterial Growth Signal: 0.11 V,
acterial Growth Signal: 0.12 V,
acterial Growth Signal: 0.12 V,
acterial Growth Signal: 0.13 V,
acterial Growth Signal: 0.13 V,
acterial Growth Signal: 0.13 V,


s
1s
2s
3s
4s
5s
6s
7s
8s
9s
10s


Draft1
R2
10m
V1
cap
10µ
12
U1
R1
10k
OP07
V2
12
V5
10
Rinv
10k
V4
Rf
10k
12
U2
V3
OP07
12
.tran 0 10 0 0.1

Thank you!