# VDP_lorenzx

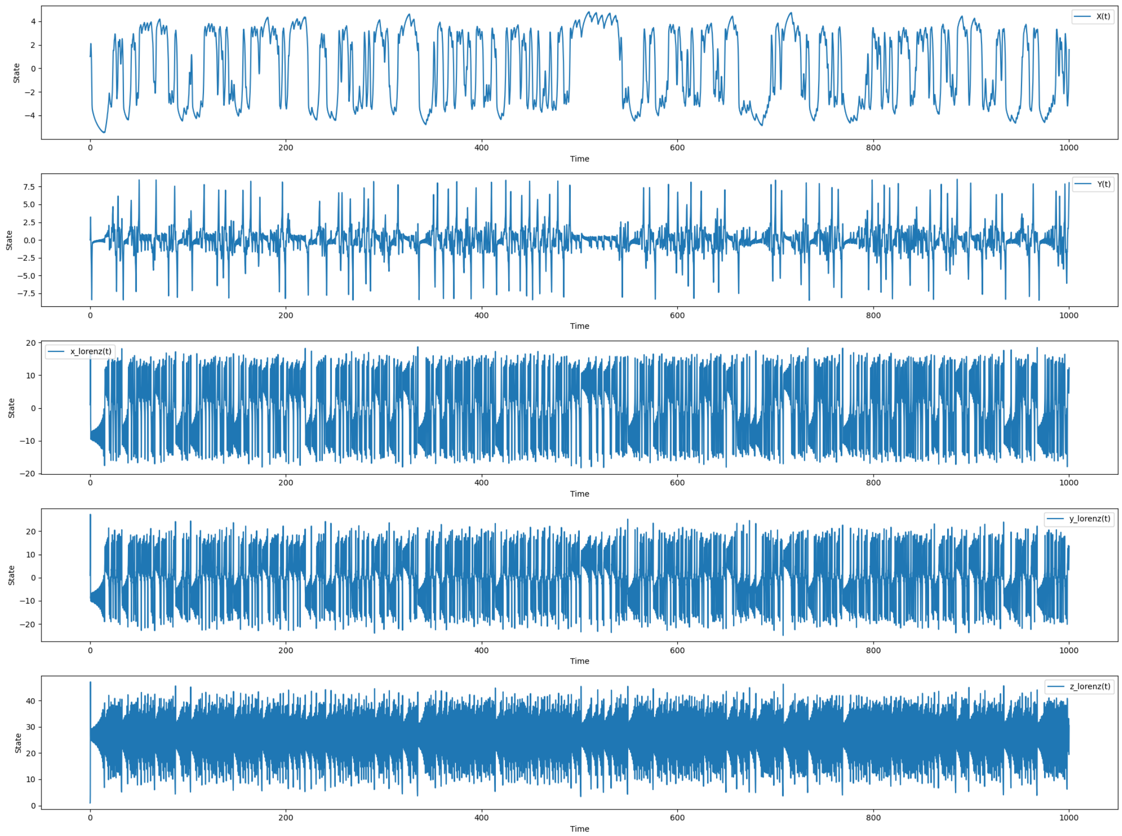
October 11, 2023

[ ]:
```python
import numpy as np
from scipy.integrate import solve_ivp
import pandas as pd
import matplotlib.pyplot as plt
from reservoirpy.observables import nrmse, rsquare

import reservoirpy as rpy

# just a little tweak to center the plots, nothing to worry about
from IPython.core.display import HTML
HTML("""
<style>
.img-center {
    display: block;
    margin-left: auto;
    margin-right: auto;
    }
.output_png {
    display: table-cell;
    text-align: center;
    vertical-align: middle;
    }
</style>
""")

rpy.set_seed(42)

rpy.verbosity(0)

from reservoirpy.nodes import Reservoir, Ridge
from reservoirpy.datasets import mackey_glass
```

[ ]:
```python
import numpy as np
from scipy.integrate import solve_ivp
import matplotlib.pyplot as plt

def coupled_system(t, state, mu, sigma, rho, beta):
    X, Y, x_lorenz, y_lorenz, z_lorenz = state
```

```
    dXdt = Y
    dYdt = mu * (1 - X**2) * Y - X + x_lorenz

    dx_lorenz_dt = sigma * (y_lorenz - x_lorenz)
    dy_lorenz_dt = x_lorenz * (rho - z_lorenz) - y_lorenz
    dz_lorenz_dt = x_lorenz * y_lorenz - beta * z_lorenz

    return [dXdt, dYdt, dx_lorenz_dt, dy_lorenz_dt, dz_lorenz_dt]

mu = 1.0
sigma = 10.0
rho = 28.0
beta = 8/3
initial_state = [1.0, 0.0, 1.0, 1.0, 1.0]  # Initial states for [X, Y,␣
 ↪x_lorenz, y_lorenz, z_lorenz]
t_span = (0, 1000)

sol = solve_ivp(coupled_system, t_span, initial_state, args=(mu, sigma, rho,␣
 ↪beta), t_eval=np.linspace(t_span[0], t_span[1], 10000))

# Plot the results
plt.figure(figsize=(20, 15))

plt.subplot(5, 1, 1)
plt.plot(sol.t, sol.y[0], label='X(t)')
plt.xlabel('Time')
plt.ylabel('State')
plt.legend()

plt.subplot(5, 1, 2)
plt.plot(sol.t, sol.y[1], label='Y(t)')
plt.xlabel('Time')
plt.ylabel('State')
plt.legend()

plt.subplot(5, 1, 3)
plt.plot(sol.t, sol.y[2], label='x_lorenz(t)')
plt.xlabel('Time')
plt.ylabel('State')
plt.legend()

plt.subplot(5, 1, 4)
plt.plot(sol.t, sol.y[3], label='y_lorenz(t)')
plt.xlabel('Time')
plt.ylabel('State')
plt.legend()
```

```python
plt.subplot(5, 1, 5)
plt.plot(sol.t, sol.y[4], label='z_lorenz(t)')
plt.xlabel('Time')
plt.ylabel('State')
plt.legend()

plt.tight_layout()
plt.show()
```




[ ]:
```python
#Time, Van Der Pol  Oscillator X, lorenz x

data = pd.DataFrame({
    'Time': sol.t,
    'X': sol.y[0],
    'x_lorenz': sol.y[2]
})

# DataFrame CSV
data.to_csv('coupled_system_dataset.csv', index=False)
```

[ ]:
```
data_loaded = pd.read_csv('forced_vanderpol_dataset.csv')
```

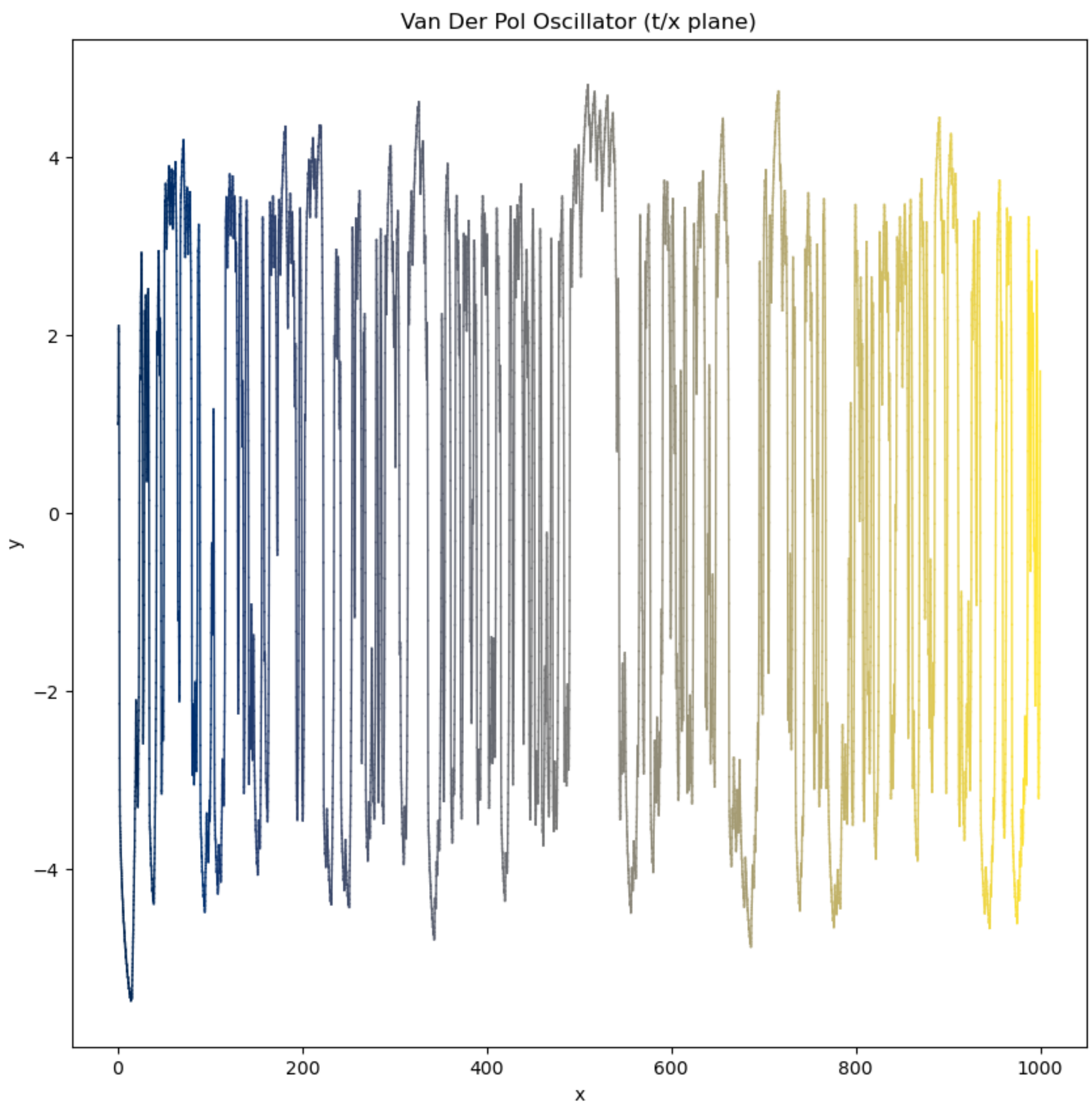
[ ]:
```
X = data.values
```

[ ]:
```
X.shape
```

[ ]:
```
(10000, 3)
```

[ ]:
```
def plot_vanderpol_2d(X, timesteps):
    # 2D
    fig, ax = plt.subplots(figsize=(10, 10))
    ax.set_title("Van Der Pol Oscillator (t/x plane)")
    ax.set_xlabel("x")
    ax.set_ylabel("y")

    #
    for i in range(timesteps-1):
        ax.plot(X[i:i+2, 0], X[i:i+2, 1], color=plt.cm.cividis(255*i//
 ↪timesteps), lw=1.0)

    plt.show()
```

[ ]:
```
plot_vanderpol_2d(X, 10000)
```




# 1 esn fitting

[ ]:
```
X = X[:, 1]

#z-score normalization
X = (X - np.mean(X)) / np.std(X)
```

[ ]:
```
X = X.reshape(-1, 1)
X.shape
```

[ ]: (10000, 1)

[ ]:
```
X
```

[ ]:
```
array([[0.32261709],
       [0.3229254 ],
       [0.32770749],
       …,
       [0.03927255],
       [0.26074807],
       [0.51432419]])
```

[ ]:
```
from reservoirpy.datasets import to_forecasting

#1
X, Y = to_forecasting(X, forecast=1)
X_train1, Y_train1 = X[:1000], Y[:1000]
X_test1, Y_test1 = X[1000:], Y[1000:]
```

[ ]:
```
#
units = 500
leak_rate = 0.17113764962939737
spectral_radius = 1.182082887824895
input_scaling = 0.9697295578201843
connectivity = 0.10407566959031667      # - density of reservoir internal matrix
input_connectivity = 0.2  # and of reservoir input matrix
regularization = 5.602814683095597e-09
seed = 1234              # for reproducibility
```

[ ]:
```
def reset_esn():
    from reservoirpy.nodes import Reservoir, Ridge

    reservoir = Reservoir(units, input_scaling=input_scaling,␣
↪sr=spectral_radius,
                          lr=leak_rate, rc_connectivity=connectivity,
                          input_connectivity=input_connectivity, seed=seed)
    readout   = Ridge(1, ridge=regularization)

    return reservoir >> readout
```

[ ]:
```
from reservoirpy.nodes import Reservoir, Ridge

reservoir = Reservoir(units, input_scaling=input_scaling, sr=spectral_radius,
                      lr=leak_rate, rc_connectivity=connectivity,
                      input_connectivity=input_connectivity, seed=seed)
readout   = Ridge(1, ridge=regularization)

esn = reservoir >> readout
```

[ ]:
```python
y = esn(X[0])  # initialisation
reservoir.Win is not None, reservoir.W is not None, readout.Wout is not None
```

[ ]:
```
(True, True, True)
```

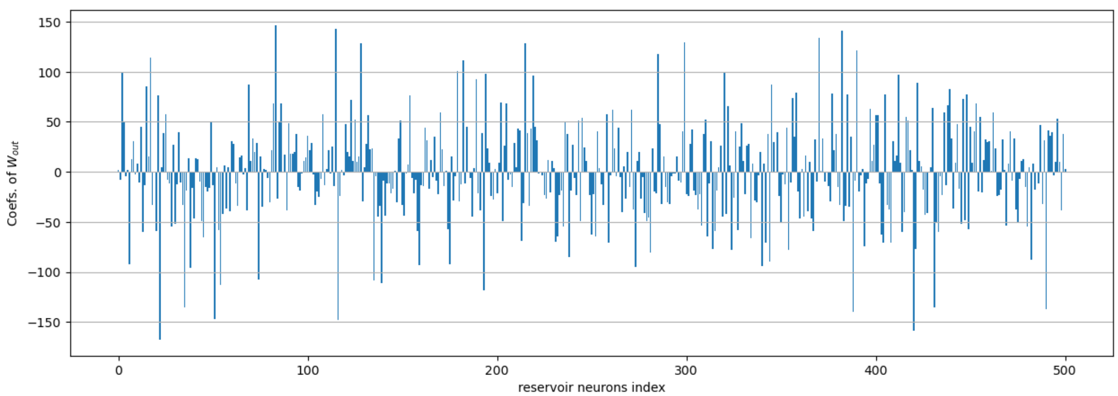
[ ]:
```python
np.all(readout.Wout == 0.0)
```

[ ]:
```
True
```

[ ]:
```python
esn = esn.fit(X_train1, Y_train1, warmup=100)
```

[ ]:
```python
def plot_readout(readout):
    Wout = readout.Wout
    bias = readout.bias
    Wout = np.r_[bias, Wout]

    fig = plt.figure(figsize=(15, 5))

    ax = fig.add_subplot(111)
    ax.grid(axis="y")
    ax.set_ylabel("Coefs. of $W_{out}$")
    ax.set_xlabel("reservoir neurons index")
    ax.bar(np.arange(Wout.size), Wout.ravel()[::-1])

    plt.show()
```

[ ]:
```python
plot_readout(readout)
```



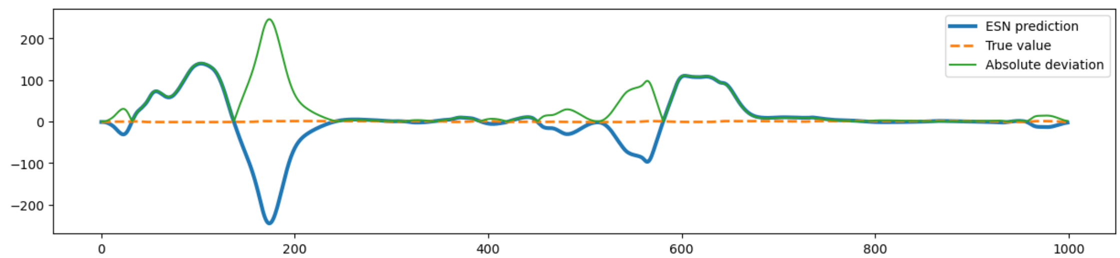

[ ]:
```python
def plot_results(y_pred, y_test, sample=1000):

    fig = plt.figure(figsize=(15, 7))
    plt.subplot(211)
    plt.plot(np.arange(sample), y_pred[:sample], lw=3, label="ESN prediction")
```

```python
    plt.plot(np.arange(sample), y_test[:sample], linestyle="--", lw=2, label="True value")
    plt.plot(np.abs(y_test[:sample] - y_pred[:sample]), label="Absolute deviation")

    plt.legend()
    plt.show()
```

[ ]:
```python
Y_pred1 = esn.run(X_test1)
```

## 2 RC

[ ]:
```python
plot_results(Y_pred1, Y_test1)
```




[ ]:
```python
rsquare(Y_test1, Y_pred1), nrmse(Y_test1, Y_pred1)
```

[ ]: (-2102.3865272720186, 14.545452155873795)

# 3 nrmse 14.545452155873795

### 3.1 spectral_radius, leak_rate, input_scaling, regularization, connectivity.

[ ]:
```python
def objective(dataset, config, *, cell_number, leak_rate, spectral_radius, input_connectivity, input_scaling, connectivity, regularization, seed):

    X, Y = to_forecasting(dataset, forecast=10)
    X_train1, Y_train1 = X[:1000], Y[:1000]
    X_test1, Y_test1 = X[1000:], Y[1000:]

    instances = config["instances_per_trial"]

    variable_seed = seed

    losses = []; r2s = [];
```

```
    for n in range(instances):
        reservoir = Reservoir(cell_number, input_scaling=input_scaling,␣
↪sr=spectral_radius,
                            lr=leak_rate, rc_connectivity=connectivity,
                            input_connectivity=input_connectivity, seed=seed)

        readout   = Ridge(1, ridge=regularization)

        esn = reservoir >> readout

        esn = esn.fit(X_train1, Y_train1, warmup=100)

        Y_pred1 = esn.run(X_test1)

        loss = nrmse(Y_test1, Y_pred1)
        r2 = rsquare(Y_test1, Y_pred1)

        losses.append(loss)
        r2s.append(r2)

    return {'loss': np.mean(losses),
            'r2': np.mean(r2s)}
```

[ ]:
```
hyperopt_config = {
    "exp": f"hyperopt-MG-onestep-prediction", # the experimentation name
    "hp_max_evals": 200,             # the number of differents sets of␣
↪parameters hyperopt has to try
    "hp_method": "random",           # the method used by hyperopt to chose␣
↪those sets (see below)
    "seed": 42,                      # the random state seed, to ensure␣
↪reproducibility
    "instances_per_trial": 3,        # how many random ESN will be tried with␣
↪each sets of parameters
    "hp_space": {                    # what are the ranges of parameters␣
↪explored
        "cell_number": ["choice", 500],             # the number of neurons is␣
↪fixed to 500
        "spectral_radius": ["loguniform", 1e-2, 10],   # the spectral radius is␣
↪log-uniformly distributed between 1e-2 and 10
        "leak_rate": ["loguniform", 1e-3, 1],  # idem with the leaking rate,␣
↪from 1e-3 to 1
        "input_scaling": ["uniform", 0, 1],           # the input scaling␣
↪uniformly distributed between 0 and 1
        "input_connectivity": ["choice", 0.2], # the number of neurons is fixed␣
↪to 0.2
```

```
        "regularization": ["loguniform", 1e-10, 1],  # the regularization␣
↪parameter is log-uniformly distributed between 1e-10 and 1.
        "connectivity": ["uniform", 0, 1], # the connectivity of the random␣
↪network in the hidden layer uniformly distributed between 0 and 1.
        "seed": ["choice", 1234]          # an other random seed for the ESN␣
↪initialization
    }
}



import json

# we precautionously save the configuration in a JSON file
# each file will begin with a number corresponding to the current␣
↪experimentation run number.
with open(f"{hyperopt_config['exp']}.config.json", "w+") as f:
    json.dump(hyperopt_config, f)
```

[ ]:
```
from reservoirpy.hyper import research

best = research(objective, X, f"{hyperopt_config['exp']}.config.json", ".")
```

```
100%|      | 200/200 [20:52<00:00,  6.26s/trial, best loss:
0.11718737488530 44]
```

[ ]:
```
best
```

[ ]:
```
({'cell_number': 0,
  'connectivity': 0.9548228482666989,
  'input_connectivity': 0,
  'input_scaling': 0.5933563673798359,
  'leak_rate': 0.8382221591273349,
  'regularization': 2.236024179842572e-06,
  'seed': 0,
  'spectral_radius': 0.7323231724059845},
 <hyperopt.base.Trials at 0x297971b50>)
```

# 4 hyperparameters esn fitting

[ ]:
```
#
units = 500
leak_rate = 0.8382221591273349
spectral_radius = 0.7323231724059845
input_scaling = 0.5933563673798359
connectivity = 0.9548228482666989       # - density of reservoir internal matrix
input_connectivity = 0.2  # and of reservoir input matrix
regularization = 2.236024179842572e-06
```

```
seed = 1234              # for reproducibility
```

[ ]:
```
from reservoirpy.nodes import Reservoir, Ridge

reservoir = Reservoir(units, input_scaling=input_scaling, sr=spectral_radius,
                      lr=leak_rate, rc_connectivity=connectivity,
                      input_connectivity=input_connectivity, seed=seed)
readout   = Ridge(1, ridge=regularization)

esn = reservoir >> readout
```

[ ]:
```
y = esn(X[0])  # initialisation
reservoir.Win is not None, reservoir.W is not None, readout.Wout is not None
```

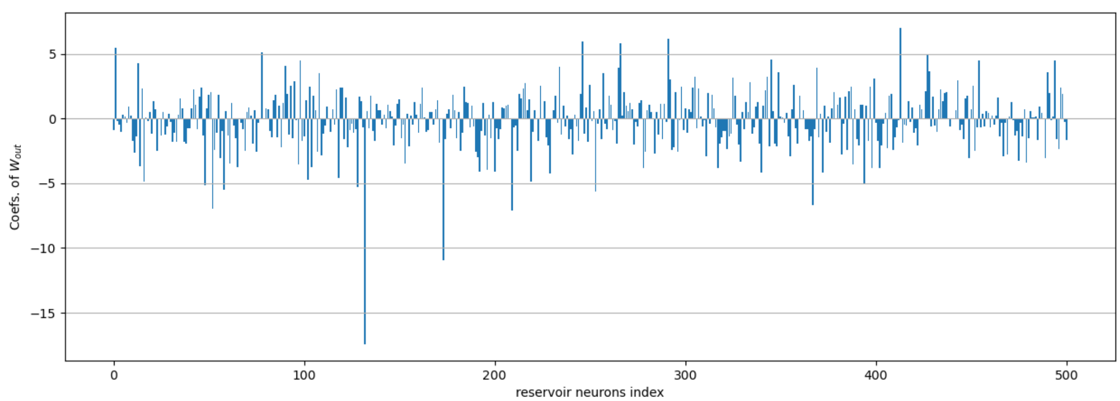
[ ]: (True, True, True)

[ ]:
```
np.all(readout.Wout == 0.0)
```

[ ]: True

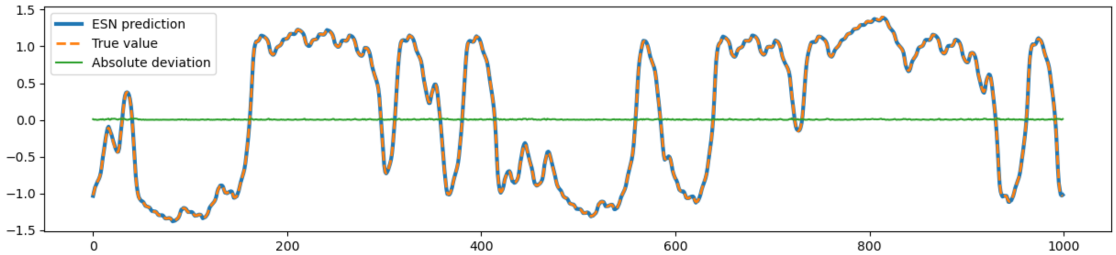
[ ]:
```
esn = esn.fit(X_train1, Y_train1, warmup=100)
```

[ ]:
```
#W_out
plot_readout(readout)
```




[ ]:
```
Y_pred1 = esn.run(X_test1)
```

[ ]:
```
plot_results(Y_pred1, Y_test1)
```




```
[ ]: rsquare(Y_test1, Y_pred1), nrmse(Y_test1, Y_pred1)
```

```
[ ]: (0.9999515001268733, 0.0022087063689438216)
```

# 5 nrmse 0.0022087063689438216

14.545452155873795

```
[ ]: X_test1.shape
```

```
[ ]: (8999, 1)
```

# 6 X Y_pred1

```
[ ]: Y_pred1[-10:]
```

```
[ ]: array([[-0.75039814],
            [-0.69751703],
            [-0.63477833],
            [-0.54839908],
            [-0.43259336],
            [-0.29977342],
            [-0.15150833],
            [ 0.03041797],
            [ 0.24860936],
            [ 0.5010843 ]])
```

```
[ ]: X[-9:]
```

```
[ ]: array([[-0.74533189],
            [-0.69160057],
            [-0.6266132 ],
            [-0.54082037],
            [-0.43050355],
            [-0.29857988],
            [-0.14443869],
```

```
[ 0.03927255],
[ 0.26074807]])
```