

# Sample Assignment

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## Question 1

a)

The analytical derivative of

$$f(x) = 1 + x^2 - \sin(\pi x)$$

is

$$\frac{df(x)}{dx} = 0 + 2x - \cos(\pi x) \frac{d}{dx}(\pi x) \quad (1)$$

$$= 2x - \pi \cos(\pi x). \quad (2)$$

b)

Plots of the analytical and finite difference derivatives of  $f(x)$  are found below.

```
In [1]: # Imports

import numpy as np
import scipy.integrate
import scipy.linalg
from matplotlib import pyplot as plt
```

```
In [2]: # Function definitions for plots

def f(x: np.ndarray) -> np.ndarray:
    """Evaluate function (1).

    Parameters
    -----
    x : np.ndarray
        Function input.

    Returns
    -----
    np.ndarray
        Function value.
    """
    y = 1 + x**2 - np.sin(np.pi * x)
```

```

    return y

def f_dot_analytical(x: np.ndarray) -> np.ndarray:
    """Evaluate analytical derivative of (1).

    Parameters
    -----
    x : np.ndarray
        Function input.

    Returns
    -----
    np.ndarray
        Derivative value.
    """
    y_dot = (2 * x) - np.pi * np.cos(np.pi * x)
    return y_dot

def f_dot_finite_difference(x: np.ndarray, delta_x: float) -> np.ndarray:
    """Evaluate forward finite difference approximation of derivative of (1).

    Parameters
    -----
    x : np.ndarray
        Function input.
    delta_x : float
        Step size.

    Returns
    -----
    np.ndarray
        Derivative value.
    """
    y_dot = (f(x + delta_x) - f(x)) / delta_x
    return y_dot

```

```

In [3]: # Create array of ``x`` values to evaluate
x = np.arange(0, 5, 1e-1)
# Compute derivative of ``f`` using both methods, evaluated at ``x``
f_dot_an_x = f_dot_analytical(x)
f_dot_fd_x = f_dot_finite_difference(x, delta_x=1)

```

```

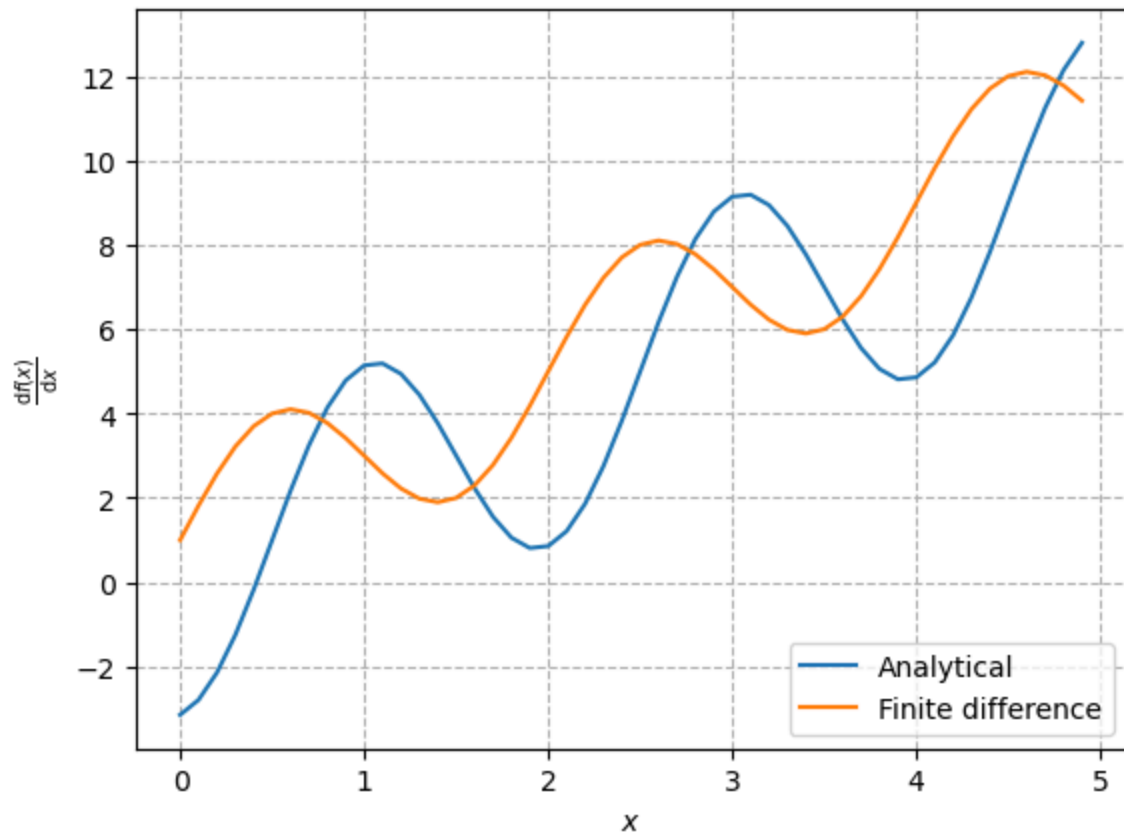
In [4]: # Plot derivatives for 1b)
fig, ax = plt.subplots()
ax.plot(x, f_dot_an_x, label='Analytical')
ax.plot(x, f_dot_fd_x, label='Finite difference')
ax.set_xlabel(r'$x$')
ax.set_ylabel(r'$\frac{\mathrm{d}f(x)}{\mathrm{d}x}$')
ax.grid(linestyle='--')
ax.legend(loc='lower right')

```

```

Out[4]: <matplotlib.legend.Legend at 0x7f218420a390>

```

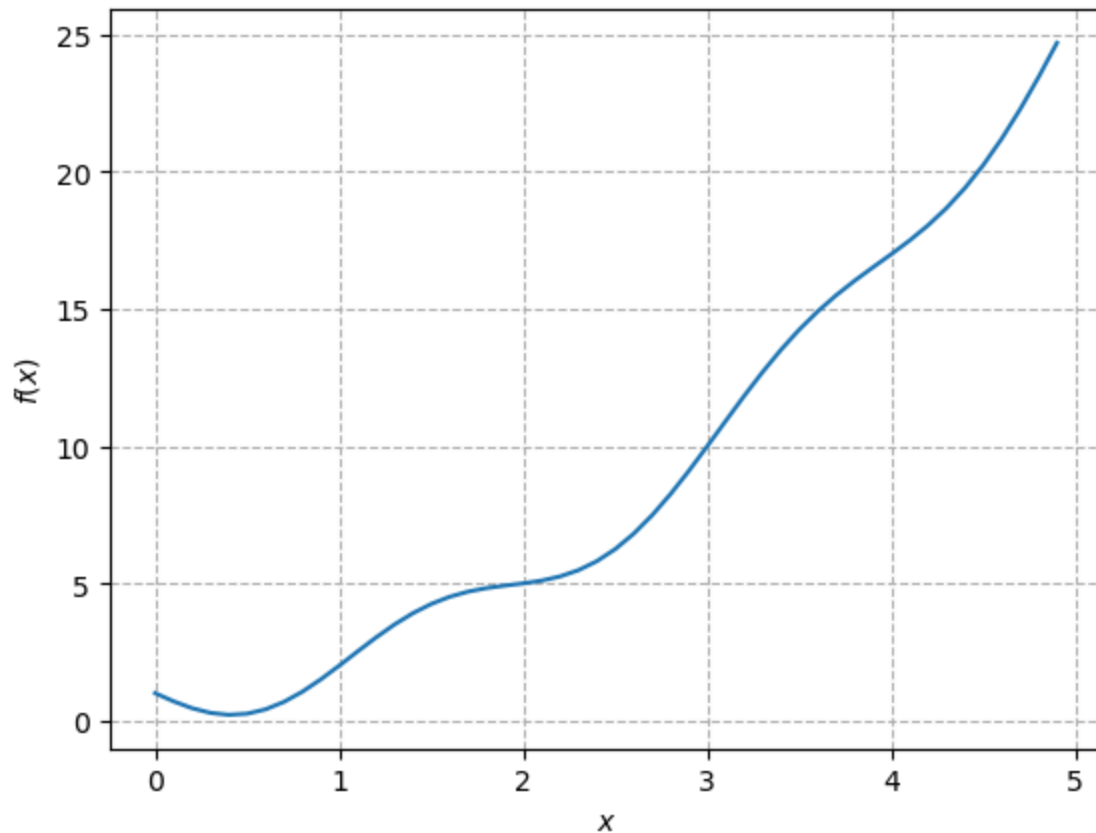


c)

A plot of  $f(x)$  for  $x \in [0, 5]$  is found below.

```
In [5]: # Evaluate ``f(x)`` using ``x`` defined above.
f_x = f(x)
```

```
In [6]: # Plot function for 1c)
fig, ax = plt.subplots()
ax.plot(x, f_x)
ax.set_xlabel(r'$x$')
ax.set_ylabel(r'$f(x)$')
ax.grid(linestyle='--')
```



The figure above shows that  $\Delta x = 1$  is not an appropriate step size for  $f(x)$ , as it is too large. The derivative near zero should be negative, but since the step size is too large, it is incorrectly approximated as positive. In this case, a good rule of thumb would be to pick  $\Delta x$  to be significantly smaller than the period of  $\sin(\pi x)$ .

## Question 2

a)

The eigenvalues of  $\mathbf{A}$  are

$$\lambda_0 = -0.25 + j0.19364917, \quad (3)$$

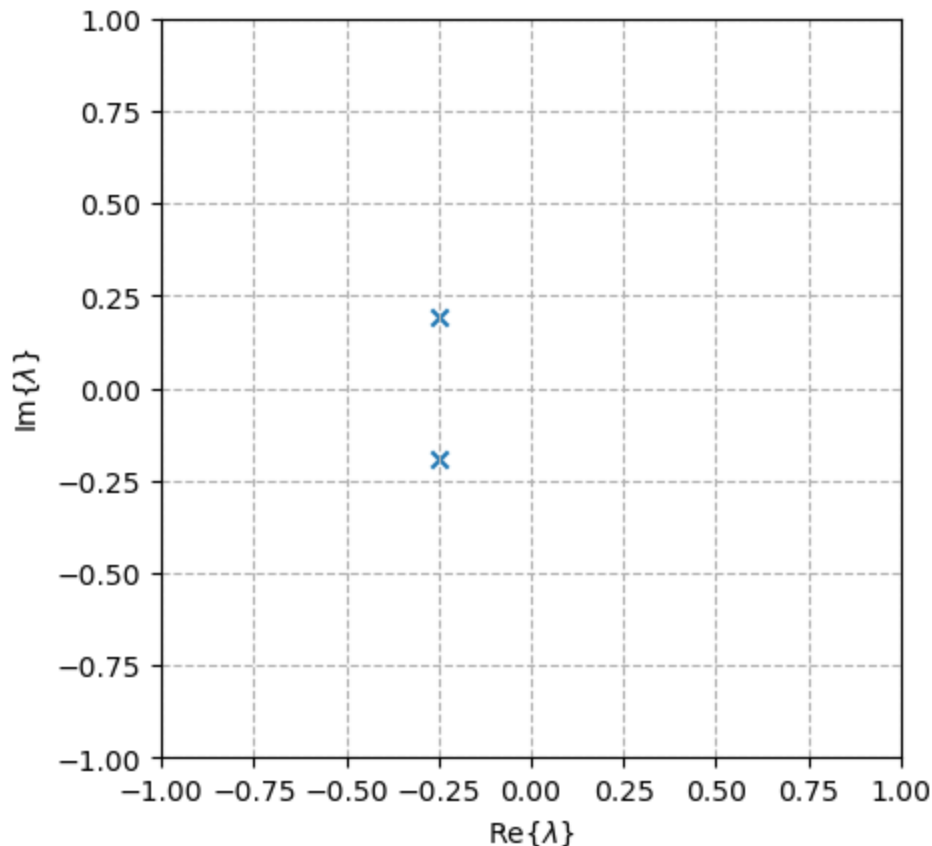
$$\lambda_1 = -0.25 - j0.19364917, \quad (4)$$

as computed with `scipy.linalg.eigvals()`. They are plotted below.

```
In [7]: # Compute eigenvalues
A = np.array([
    [0, 1],
    [-0.1, -0.5],
])
eigv = scipy.linalg.eigvals(A)
print(eigv)
```

```
[-0.25+0.19364917j -0.25-0.19364917j]
```

```
In [8]: # Plot eigenvalues
fig, ax = plt.subplots()
ax.scatter(np.real(eigv), np.imag(eigv), marker='x')
ax.set_xlim([-1, 1])
ax.set_ylim([-1, 1])
ax.set_aspect('equal') # Force axis aspect ratio to be equal
ax.set_xlabel(r'$\mathrm{Re}\{\lambda\}$')
ax.set_ylabel(r'$\mathrm{Im}\{\lambda\}$')
ax.grid(linestyle='--')
```



**b)**

The ODE is asymptotically stable because its eigenvalues are in the open left half-plane. In other words, their real parts are strictly negative.

**c)**

The numerically integrated trajectory for  $\mathbf{x}_0 = [1 \ 1]^T$

```
In [9]: def ivp(t, x):
        """Evaluate ``x_dot`` in (2)."""
        x_dot = A @ x.reshape((-1, 1))
        return x_dot.ravel()

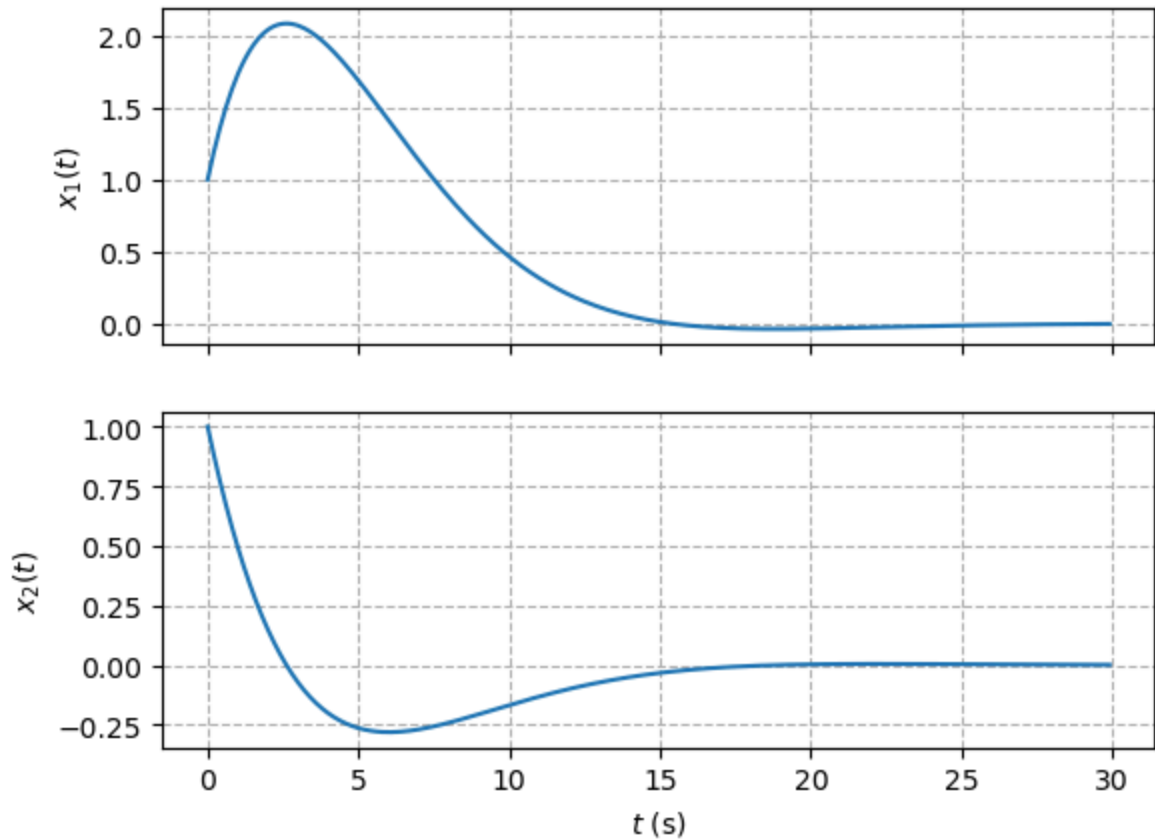
        # Solve initial value problem defined in ``ivp``
        t_span = (0, 30)
```

```

t_step = 1e-1
t = np.arange(*t_span, t_step)
x0 = np.array([1, 1])
sol = scipy.integrate.solve_ivp(
    ivp,
    t_span=t_span,
    y0=x0,
    method='RK45',
    t_eval=t,
)

# Plot trajectory
fig, ax = plt.subplots(2, 1, sharex=True)
ax[0].plot(t, sol.y[0, :])
ax[1].plot(t, sol.y[1, :])
ax[1].set_xlabel(r'$t$ (s)')
ax[0].set_ylabel(r'$x_1(t)$')
ax[1].set_ylabel(r'$x_2(t)$')
ax[0].grid(linestyle='--')
ax[1].grid(linestyle='--')

```



In [ ]: