

Homework 3

Due Date: October 27, 2025

1 - Hermite Interpolation

Given the function

$$f(x) = \frac{1}{1 + 25x^2}, \quad x \in [-1, 1],$$

with the function values and first derivatives at the nodes

$$x_0 = -1, \quad x_1 = 0, \quad x_2 = 1$$

Question 1.1

Construct the cubic Hermite interpolant $H(x)$ and evaluate $H(0.5)$.

Solution. The cubic Hermite interpolant on an interval $[x_0, x_1]$ is determined by the shape functions:

$$h_{00}(t) = 2t^3 - 3t^2 + 1, \quad h_{01}(t) = -2t^3 + 3t^2$$

$$h_{10}(t) = t^3 - 2t^2 + t, \quad h_{11}(t) = t^3 - t^2$$

Provided $h = x_1 - x_0$ and $t = \frac{x - x_0}{h} \in [0, 1]$. The cubic Hermite interpolant is given by:

$$H(x) = f(x_0)h_{00}(t) + f(x_1)h_{01}(t) + h[f'(x_0)h_{10}(t) + f'(x_1)h_{11}(t)]$$

We will construct the Hermite interpolant piecewise on the intervals $[-1, 0]$ and $[0, 1]$.

To start off with, the following table summarizes the function and derivative values at the nodes:

Node x_j	$f(x_j)$	$f'(x_j)$
-1	$\frac{1}{26}$	$\frac{50}{676} = \frac{25}{338}$
0	1	0
1	$\frac{1}{26}$	$-\frac{25}{338}$

Where $f'(x) = \frac{-50x}{(1+25x^2)^2}$.

On $[-1, 0]$, we have $h = 1$ and $t = x + 1$. So therefore we have:

$$h_{00}(x + 1) = 2(x + 1)^3 - 3(x + 1)^2 + 1 = 2x^3 + 3x^2$$

$$h_{01}(x + 1) = -2(x + 1)^3 + 3(x + 1)^2 = -2x^3 - 3x^2 + 1$$

$$h_{10}(x+1) = (x+1)^3 - 2(x+1)^2 + (x+1) = x^3 + x^2$$

$$h_{11}(x+1) = (x+1)^3 - (x+1)^2 = x^3 + 2x^2 + x$$

Substituting into the interpolant formula, we get:

$$H(x) = \frac{1}{26}(2x^3 + 3x^2) + 1(-2x^3 - 3x^2 + 1) + 1 \cdot \frac{25}{338}(x^3 + x^2) + 0$$

Simplifying, we have:

$$H(x) = -\frac{625}{338}x^3 - \frac{475}{169}x^2 + 1, \quad x \in [-1, 0]$$

On $[0, 1]$, we have $h = 1$ and $t = x$. So therefore our shape functions are as defined initially with x in place of t . Substituting into the interpolant formula, we get:

$$H(x) = 1(2x^3 - 3x^2 + 1) + \frac{1}{26}(-2x^3 + 3x^2) + 0 - \frac{25}{338}(x^3 - x^2)$$

Simplifying, we have:

$$H(x) = \frac{625}{338}x^3 - \frac{475}{169}x^2 + 1, \quad x \in [0, 1]$$

So the cubic Hermite interpolant is:

$$H(x) = \begin{cases} -\frac{625}{338}x^3 - \frac{475}{169}x^2 + 1, & x \in [-1, 0] \\ \frac{625}{338}x^3 - \frac{475}{169}x^2 + 1, & x \in [0, 1] \end{cases}$$

Evaluating at $x = 0.5$, we get that:

$$H(0.5) = \frac{625}{338}(0.5)^3 - \frac{475}{169}(0.5)^2 + 1 = \frac{1429}{2704} \approx 0.528479290$$

Question 1.2

Evaluate the absolute error of $f(0.5) - H(0.5)$, and show that the error agrees the prior estimate of

$$f(x) - p(x) = \frac{f^{(2n+2)}(\xi)}{(2n+2)!} \prod_{j=0}^n (x - x_j)^2$$

for some ξ between x and x_j .

Solution. Note that $f(0.5) = \frac{4}{29} \approx 0.1379310345$.

The absolute error with our estimate $H(0.5)$ is:

$$|f(0.5) - H(0.5)| = \left| \frac{4}{29} - \frac{1429}{2704} \right| = \frac{30625}{78416} \approx 0.390548$$

The fourth derivative of $f(x)$ is:

$$f^{(4)}(x) = \frac{15000(3125x^4 - 250x^2 + 1)}{(25x^2 + 1)^5}$$

The maximum of $|f^{(4)}(\xi)|$ for $\xi \in [-1, 1]$ occurs at $x = 0$, yielding:

$$|f^{(4)}(0)| = 15000$$

The product term evaluated at $x = 0.5$ is:

$$\prod_{j=1}^2 (0.5 - x_j)^2 = (0.5 - 0)^2 (0.5 - 1)^2 = \left(\frac{1}{2}\right)^2 \cdot \left(-\frac{1}{2}\right)^2 = \frac{1}{4} \cdot \frac{1}{4} = \frac{1}{16}$$

We also have that $(2n+2)! = 4! = 24$ for $n = 1$. So putting everything together, we can estimate the error as:

$$|f(0.5) - H(0.5)| \leq \frac{15000}{24} \cdot \frac{1}{16} = \frac{625}{16} \approx 39.0625$$

So therefore our absolute error is well within the established bound.

Extra: Absolute Error with Standard Hermite Interpolant

Note: Question 1.1 was originally done by hand with the regular Hermite Interpolant resulting in a polynomial of degree 5. This was the error analysis conducted for that version.

The absolute error with our estimate $P_5(0.5)$ is:

$$|f(0.5) - P_5(0.5)| = \left| \frac{4}{29} - \frac{6341}{10816} \right| = \frac{140625}{313664} \approx 0.4483300602$$

To estimate the error using the provided formula, we first need to compute the sixth derivative of $f(x)$, which works out to:

$$f^{(6)}(x) = \frac{11250000(109375x^6 - 21875x^4 + 525x^2 - 1)}{(25x^2 + 1)^7}$$

The maximum of $|f^{(6)}(\xi)|$ for $\xi \in [-1, 1]$ occurs at $x = 0$, yielding:

$$|f^{(6)}(0)| = 11250000$$

The product term evaluated at $x = 0.5$ is:

$$\prod_{j=0}^2 (0.5 - x_j)^2 = (0.5 + 1)^2 (0.5 - 0)^2 (0.5 - 1)^2 = \left(\frac{3}{2}\right)^2 \cdot \left(\frac{1}{2}\right)^2 \cdot \left(-\frac{1}{2}\right)^2 = \frac{9}{4} \cdot \frac{1}{4} \cdot \frac{1}{4} = \frac{9}{64}$$

We also have that $(2n + 2)! = 6! = 720$ for $n = 2$.

So putting everything together, we can estimate the error as:

$$|f(0.5) - P_5(0.5)| \leq \frac{11250000}{720} \cdot \frac{9}{64} = \frac{140625}{64} \approx 2197.265625$$

So therefore our absolute error is well within the established bound.

Question 1.3

Obtain the cubic Hermite interpolant in Newton form $P(x)$., by constructing the Hermite divided-difference table.

Solution. The code for Lagrange Interpolation from the previous assignment was modified compute the Hermite Interpolation:

Listing 1: 1.3 Python

```

1 import numpy as np
2
3 def f(x):
4     return 1 / (1 + 25 * x**2)
5
6 def f_prime(x):
7     return -50 * x / (1 + 25 * x**2)**2
8
9 def hermite_coefficients(nodes, f=f, f_prime=f_prime):
10     # Parameterize nodes for Hermite interpolation
11     z = np.concatenate((nodes, nodes))
12     sorted_indexes = z.argsort()
13     z = z[sorted_indexes]
14     num_nodes = len(z)
15
16     # Set up dd table with zeroth dd
17     dd_table = np.array([[f(zi) for zi in z]])
18
19     # First divided difference
20     f_prime_nodes = np.array([f_prime(xi) for xi in nodes])
21     zeros = np.zeros(len(nodes))
22     first_dd = np.concatenate((f_prime_nodes, zeros))[sorted_indexes]
23     for j in range(num_nodes - 1):
24         if j % 2 == 1:
25             first_dd[j] = (dd_table[0, j + 1] - dd_table[0, j]) / (z[j + 1] - z
[j])
26     dd_table = np.vstack([dd_table, first_dd])
27
28     # Remaining Divided Differences
29     for i in range(2, num_nodes):
30         ith_dd = np.zeros(num_nodes)
31
32         for j in range(num_nodes - i):
33             # Calculate ith divided differences
34             ith_dd[j] = (dd_table[i - 1, j + 1] - dd_table[i - 1, j]) / (z[j +
i] - z[j])
35
36     dd_table = np.vstack([dd_table, ith_dd])

```

```

37
38     coefficients = np.array([dd_table[i, 0] for i in range(dd_table.shape[0])])
39     return coefficients, dd_table.T, z
40
41 def generate_hermite(nodes, n):
42     # Get coefficients
43     a = hermite_coefficients(nodes)[0]
44     # Start with function and constant term
45     equation = f"P_{{{2*n+1}}}(x) = {a[0]}"
46     w = []
47     # Build (x - xi) terms
48     for xi in nodes:
49         if abs(xi) <= 1e-14:
50             w.append('(x)')
51         elif xi < 0:
52             w.append(f"(x + {abs(xi)})")
53         else:
54             w.append(f"(x - {xi})")
55     b = ""
56
57     # Build polynomial string
58     for i in range(1, len(a)):
59         for j in range(i):
60             # Multiply (x - xi) terms
61             b += '^2' if j%2 == 1 else w[int(j/2)]
62             # Multiply (x - xi) product with current coefficient and add term
63             if a[i] > 0:
64                 equation += f" + {a[i]}{b}"
65             elif a[i] < 0:
66                 equation += f" - {abs(a[i])}{b}"
67             b = ""
68
69     return equation
70
71 if __name__ == '__main__':
72     nodes_1 = np.array([-1,0])
73     equation_1 = generate_hermite(nodes_1, 1)
74     table_1, z_1 = hermite_coefficients(nodes_1)[1:3]
75
76     nodes_2 = np.array([0,1])
77     equation_2 = generate_hermite(nodes_1, 1)
78     table_2, z_2 = hermite_coefficients(nodes_1)[1:3]
79
80     equations = [equation_1,equation_2]
81     tables = [table_1, table_2]
82     z = [z_1,z_2]
83

```

```

84     with open("./outputs_3/hermite.txt", 'w') as file:
85         for k in range(2):
86             file.write(equations[k] + '\n\n')
87
88             file.write('\begin{center}\n')
89             file.write('\begin{tabular}{|c|c|c|c|c|}\n')
90             file.write('\hline\n')
91             file.write('& $z_i$ & $f[z_i]$ & 1st dd. & 2nd dd. & 3rd dd. \\\n
92
93             file.write('\hline\n')
94             for i in range(tables[k].shape[0]):
95                 file.write(f'$z_{i}$ & ${z[k][i]}$ ')
96                 for j in range(tables[k].shape[1]):
97                     file.write(f'& ${tables[k][i,j]:.4f}$ ')
98                 file.write('\\\\ \n')
99             file.write('\hline\n')
100            file.write('\end{tabular}\n')
            file.write('\end{center}\n\n')

```

The divided-difference tables and Hermite Interpolants generated were:

On $[-1, 0]$:

	z_i	$f[z_i]$	1st dd.	2nd dd.	3rd dd.
z_0	-1	0.0385	0.0740	0.8876	-1.8491
z_1	-1	0.0385	0.9615	-0.9615	0.0000
z_2	0	1.0000	0.0000	0.0000	0.0000
z_3	0	1.0000	0.0000	0.0000	0.0000

$$\begin{aligned}
 P_3(x) = & 0.038461538461538464 + 0.07396449704142012(x + 1) \\
 & + 0.8875739644970414(x + 1)^2 - 1.849112426035503(x + 1)^2(x)
 \end{aligned}$$

On $[0, 1]$:

	z_i	$f[z_i]$	1st dd.	2nd dd.	3rd dd.
z_0	0	1.0000	0.0000	-0.9615	1.8491
z_1	0	1.0000	-0.9615	0.8876	0.0000
z_2	1	0.0385	-0.0740	0.0000	0.0000
z_3	1	0.0385	0.0000	0.0000	0.0000

$$\begin{aligned}
 P_3(x) = & 1.0 - 0.9615384615384616(x)^2 \\
 & + 1.849112426035503(x)^2(x - 1)
 \end{aligned}$$

Question 1.4

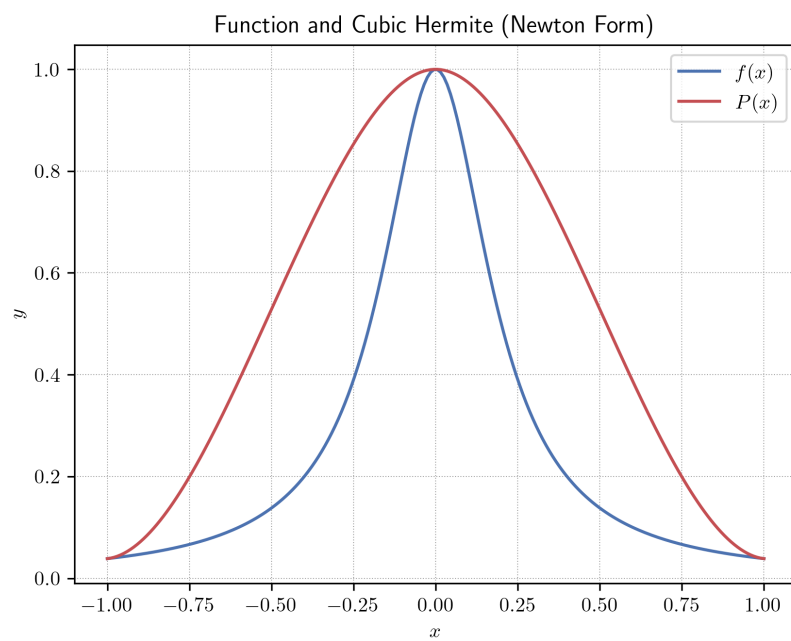
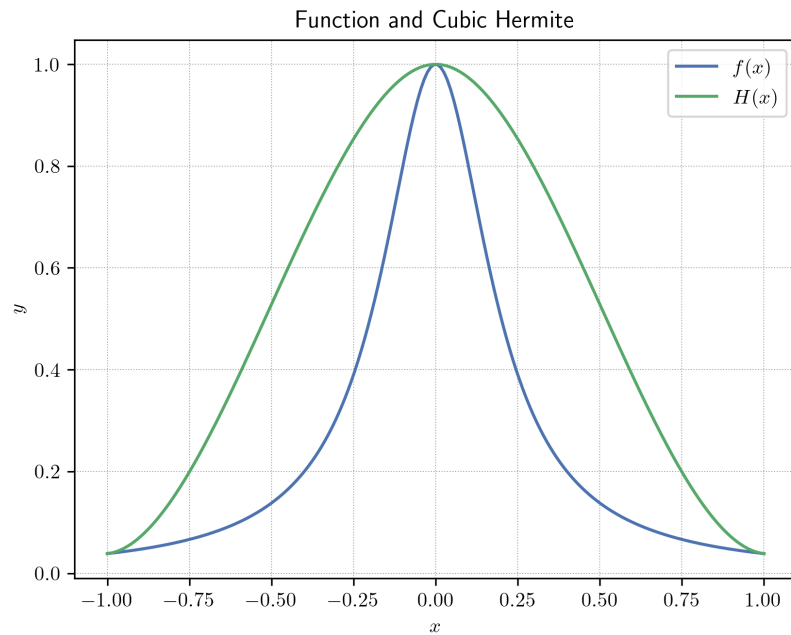
Plot $f(x)$, $H(x)$ and $P(x)$ on $x \in [-1, 1]$.

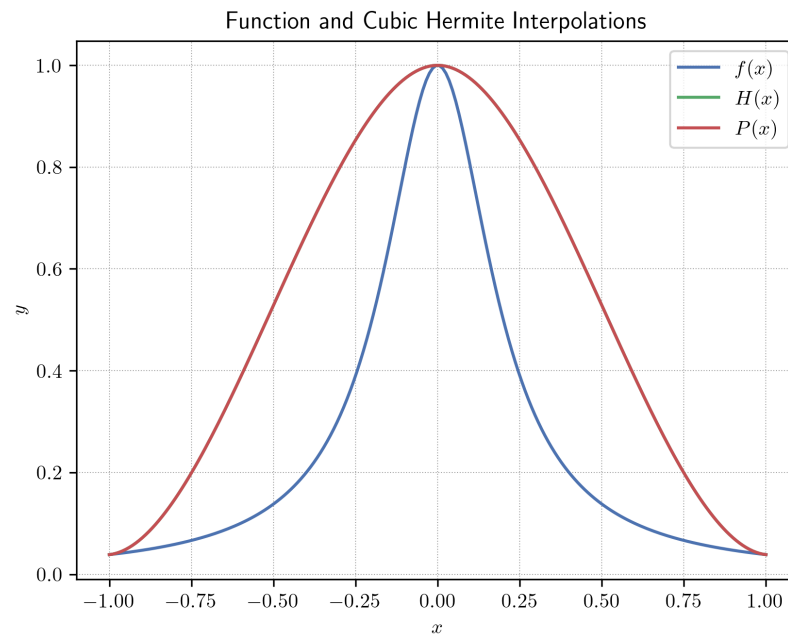
Solution. The following code was used to plot the functions:

Listing 2: 1.4 Python

```
1 import numpy as np
2 import matplotlib.pyplot as plt
3
4 if __name__ == "__main__":
5     #<Some matplotlib styling and enable LaTeX>
6     x = np.linspace(-1, 1, 200)
7     f_y = f(x)
8
9     conditions = [x <= 0, x > 0]
10    h_y = np.piecewise(x, conditions, [h_1, h_2])
11    p_y = np.concatenate(
12        (calculate_hermite(nodes_1, x[:100]), calculate_hermite(nodes_2, x
13        [100:]))
14    )
15
16    plt.plot(x, f_y, label="$f(x)$")
17    plt.plot(x, h_y, label="$H(x)$")
18    plt.xlabel("$x$")
19    plt.ylabel("$y$")
20    plt.legend()
21    plt.title("Function and Cubic Hermite")
22    plt.savefig("../outputs_3/hermite_plot_h.png", dpi=300)
23    plt.cla()
24
25    # Similar Plotting for P(x) and for all three together
```


The following plots were generated:





We observe that both Hermite interpolants $H(x)$ and $P(x)$ are identical and loosely follow the behavior of $f(x)$ on the interval $[-1, 1]$.

2 - Simple Analysis on Finite Difference

Consider the forward difference formula for the first derivative of a smooth function $f(x)$:

$$D_h f(x) = \frac{f(x+h) - f(x)}{h}$$

The total error for this approximation can be expressed as:

$$E(h) = \frac{C_1}{h} + C_2 h$$

with the optimal step size h :

$$h_{opt} = \sqrt{\frac{C_1}{C_2}}$$

where C_1 and C_2 are constants depending on $f(x)$, machine precision ε , and its derivatives.

Let $f(x) = e^x$, and take $x = 1.5$.

Question 2.1

Compute $f'(1.5)$ using the forward difference formula for a range of step sizes $h = 10^{-k}$, where $k = 1, 2, \dots, 10$.

Solution. The following code was used to compute the forward difference approximations:

Listing 3: 2.1 Python

```

1 import numpy as np
2
3 def forward_diff(f, x, step=1):
4     return (f(x + step) - f(x)) / step
5
6 if __name__ == "__main__":
7     with open("./outputs_3/forward_diff.txt", "w") as file:
8         for k in range(1,11):
9             h = 10**(-k)
10            f_prime = forward_diff(np.exp, 1.5, h)
11            file.write(f'\\[D_h^{({k})}]f(1.5) = {f_prime}\\[\\n')
```

The following results were obtained for $D_h^{(k)} f(1.5)$:

$$D_h^{(1)} f(1.5) = 4.713433540570504$$

$$D_h^{(2)} f(1.5) = 4.5041723976187775$$

$$D_h^{(3)} f(1.5) = 4.483930662008362$$

$$D_h^{(4)} f(1.5) = 4.481913162264206$$

$$D_h^{(5)} f(1.5) = 4.4817114789097445$$

$$D_h^{(6)} f(1.5) = 4.48169131139764$$

$$D_h^{(7)} f(1.5) = 4.481689304114411$$

$$D_h^{(8)} f(1.5) = 4.481689064306238$$

$$D_h^{(9)} f(1.5) = 4.481689686031132$$

$$D_h^{(10)} f(1.5) = 4.48169501510165$$

Question 2.2

Plot the absolute error $|D_h f(1) - f'(1)|$ versus h on a log-log scale. (Report code)

Solution. The following code was used to compute and plot the absolute error:

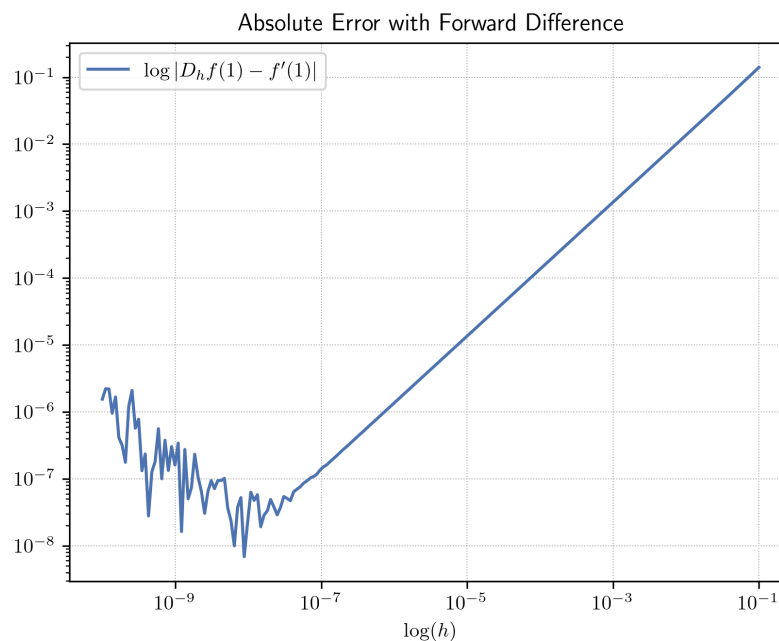
Listing 4: 2.2 Python

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3
4 def calc_absolute_error(f, step, eval_x=1, diff_method=forward_diff):
5     approx = diff_method(f, eval_x, step)
6     return np.abs(approx - f(eval_x))
7
8 if __name__ == "__main__":
9     # <Some matplotlib styling and enable LaTeX>
10    h = np.logspace(-1, -10, 200)
11    error = calc_absolute_error(np.exp, h)
12    plt.loglog(h, error, label='$\\log|D_h f(1) - f'(1)|$')
13    plt.xlabel('$\\log(h)$')
14    plt.title('Absolute Error in Forward Difference Approximation')
15    plt.legend()
16    plt.savefig('./outputs_3/forward_diff_graph.png', dpi=300)
17    plt.show()

```

The resulting plot was:



We observe that machine error starts to occur as h gets smaller than approximately than 10^{-7} .

Question 2.3

Identify the h that minimizes the total error and compare it with the predicted h_{opt} .

Solution. From the plot above, we observe that the minimum error occurs around $h \approx 10^{-8}$.

Machine error is $\varepsilon \sim 10^{-16}$ for double precision floating point numbers. From the notes, we have that $C_1 \sim \varepsilon|f(1)|$ and $C_2 \sim \frac{|f''(1)|}{2}$. This resulted in $h_{opt} \propto \sqrt{\varepsilon} \approx 10^{-8}$, which aligns with our observed minimum error point.

Question 2.4

Use the one-sided three points scheme to approximate $f'(1.5)$, and repeat question 2.2.

Solution. The one-sided three-point finite difference formula for the first derivative is given by:

$$D_h f(x) = \frac{-3f(x) + 4f(x+h) - f(x+2h)}{2h}$$

The following code was used to compute and plot the absolute error using the three-point forward difference scheme:

Listing 5: 2.4 Python

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3
4 def three_point_forward_diff(f, x, step=1):
5     return (-3 * f(x) + 4 * f(x + step) - f(x + 2 * step)) / (2 * step)
6
7 if __name__ == "__main__":
8     with open("./outputs_3/three_point_forward_diff.txt", "w") as file:
9         for k in range(1,11):
10             h = 10**(-k)
11             f_prime = three_point_forward_diff(np.exp, 1.5, h)
12             file.write(f'\\[D_h^{{{k}}}]f(1.5) = {f_prime}\\]\\n')
13
14     # <Some matplotlib styling and enable LaTeX>
15     h = np.logspace(-1, -10, 200)
16     error = calc_absolute_error(np.exp, h, diff_method=three_point_forward_diff
17 )
18
19     plt.loglog(h, error, label='$\\log|D_hf(1) - f\\'(1)|$')
20     plt.xlabel('$\\log(h)$')
21     plt.title('Absolute Error with Three Point Forward Difference')
22     plt.legend()
23     plt.savefig('./outputs_3/three_point_forward_diff_graph.png', dpi=300)
24     plt.show()

```

Our approximation results for $D_h^{(k)} f(1.5)$ are:

$$D_h^{(1)} f(1.5) = 4.465575474195327$$

$$D_h^{(2)} f(1.5) = 4.4815385550327935$$

$$D_h^{(3)} f(1.5) = 4.481687575320414$$

$$D_h^{(4)} f(1.5) = 4.481689055397808$$

$$D_h^{(5)} f(1.5) = 4.481689070257033$$

$$D_h^{(6)} f(1.5) = 4.481689070079398$$

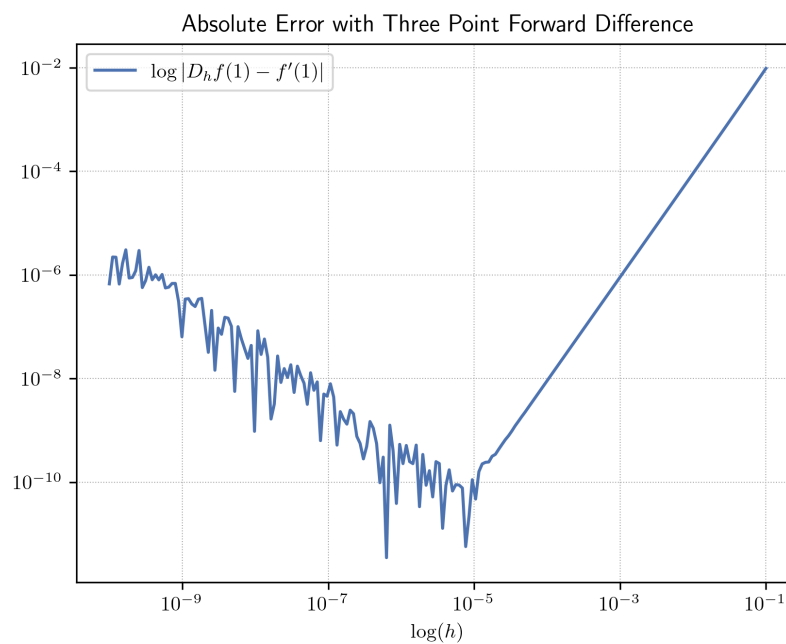
$$D_h^{(7)} f(1.5) = 4.481689086510698$$

$$D_h^{(8)} f(1.5) = 4.481688931079475$$

$$D_h^{(9)} f(1.5) = 4.481689686031132$$

$$D_h^{(10)} f(1.5) = 4.48169501510165$$

Also, the resulting plot was:



We observe that machine error starts to occur as h gets smaller than approximately 10^{-5} .

3 - Solve Burger's Equation by Finite Difference Scheme

Consider the 1D viscous Burgers' equation:

$$u_t + uu_x = \nu u_{xx}, \quad x \in [0, 1], \quad t > 0, \quad \nu = 0.2$$

Design, analyze, and implement a numerical method that is stable and achieves at least second-order accuracy in both space and time.

Question 3.1

Report finite difference scheme used.

Solution. We will be using RK4 with 2nd order finite differences for space.

First let us discretize our system. Let x_0, x_1, \dots, x_n be a partition of $[0, 1]$ with step size $\Delta x = h = \frac{1}{n}$. Let t_0, t_1, \dots, t_m be a partition of $[0, T]$ with step size Δt . Let u_i be the numerical approximation of $u(x_i, t)$.

We can construct our schemes for u_x, u_{xx} from the Taylor expansion of u centered at x_i :

$$u(x) = u(x_i) + u_x(x_i)(x - x_i) + \frac{u_{xx}(x_i)}{2}(x - x_i)^2 + \frac{u_{xxx}(x_i)}{6}(x - x_i)^3 + \dots$$

Which gives us for $x = x_i - h$ and $x = x_i + h$:

$$u(x_i - h) = u(x_i) - hu_x(x_i) + \frac{h^2}{2}u_{xx}(x_i) - \frac{h^3}{6}u_{xxx}(x_i) + O(h^4)$$

$$u(x_i + h) = u(x_i) + hu_x(x_i) + \frac{h^2}{2}u_{xx}(x_i) + \frac{h^3}{6}u_{xxx}(x_i) + O(h^4)$$

Approximate u_x centrally by:

$$u(x_i + h) - u(x_i - h) = 2hu_x(x_i) + O(h^3)$$

Which gives us the second-order scheme:

$$u_x(x_i) \approx \frac{u(x_i + h) - u(x_i - h)}{2h} + O(h^2)$$

Approximate u_{xx} with the usual second-order central difference:

$$u(x_i + h) - 2u(x_i) + u(x_i - h) = h^2u_{xx}(x_i) + O(h^4)$$

Which gives us the second-order scheme:

$$u_{xx}(x_i) \approx \frac{u(x_i + h) - 2u(x_i) + u(x_i - h)}{h^2} + O(h^2)$$

Rearranging Burger's equation for u_t , we have:

$$u_t = -uu_x + vu_{xx}$$

Substituting in our finite difference approximations, we obtain the ODE:

$$\frac{du_i}{dt} \approx -u_i \cdot \frac{u_{i+1} - u_{i-1}}{2h} + v \cdot \frac{u_{i+1} - 2u_i + u_{i-1}}{h^2} + O(h^2)$$

Which is $O(h^2) = O(\Delta x^2)$ accurate in space. Denote the right-hand side above as $F(u_i)$.

More compactly, write the system as:

$$\frac{du}{dt} = F(u) + O(\Delta x^2)$$

Where $u = [u_0, u_1, \dots, u_n]^T$.

We will now use RK4 to approximate u^{n+1} , which is given by:

$$u^{n+1} = u^n + \frac{\Delta t}{6}(k_1 + 2k_2 + 2k_3 + k_4)$$

Such that:

$$\begin{aligned} k_1 &= F(u^n) \\ k_2 &= F\left(u^n + \frac{\Delta t}{2}k_1\right) \\ k_3 &= F\left(u^n + \frac{\Delta t}{2}k_2\right) \\ k_4 &= F(u^n + \Delta tk_3) \end{aligned}$$

RK4 is $O(\Delta t^4)$ accurate in time, so our overall scheme is $O(\Delta t^4) + O(\Delta x^2)$. We also note that RK4 would have CFL conditions for stability:

$$\Delta t \leq \frac{C_1 \Delta x}{\max |u|}, \quad \Delta t \leq \frac{C_2 \Delta x^2}{v}$$

Where C_1, C_2 are constants depending on the scheme. In practice, we can choose Δt based on the more restrictive of the two conditions above and pick smaller C_1, C_2 to be safe.

Question 3.2

Use the initial condition as a sine wave $\sin(2\pi x)$. Implement the scheme and plot the numerical solution at $T = 1$ second.

Solution. We have Burger's equation:

$$u_t + uu_x = vu_{xx}, \quad x \in [0, 1], \quad t > 0, \quad v = 0.2$$

With periodic initial condition:

$$u(x, 0) = \sin(2\pi x)$$

This means that $u(0, t) = u(1, t)$ for all $t \geq 0$. Since our data is periodic, no extra scheme is needed for the boundaries and we can just treat u as a circular array.

The following code was used to implement the scheme:

Listing 6: 3.2 Python

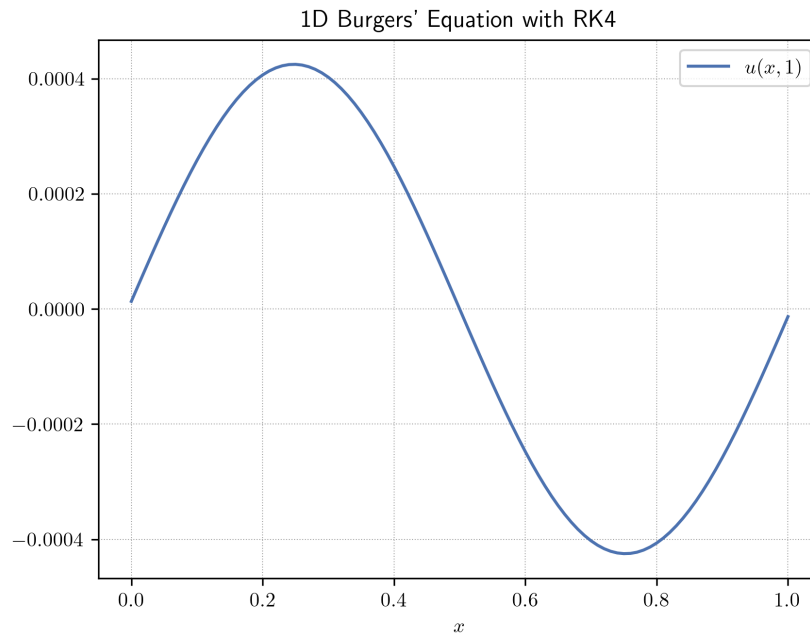
```

1 import numpy as np
2 import matplotlib.pyplot as plt
3 from copy import deepcopy
4
5 def initial_condition(x):
6     return np.sin(2 * np.pi * x)
7
8 def rk4_step(u, dt, dx, v):
9     def F(u):
10         # Compute spatial derivatives using central differences
11         u_x = (np.roll(u, -1) - np.roll(u, 1)) / (2 * dx)
12         u_xx = (np.roll(u, -1) - 2 * u + np.roll(u, 1)) / (dx**2)
13         return -u * u_x + v * u_xx
14
15     k1 = F(u)
16     k2 = F(u + 0.5 * dt * k1)
17     k3 = F(u + 0.5 * dt * k2)
18     k4 = F(u + dt * k3)
19
20     return u + (dt / 6) * (k1 + 2 * k2 + 2 * k3 + k4)
21
22 def burgers_rk4(dx, t_final, v=0.2, start_x=0, end_x=1, return_history=False):
23     # Take ceil for num_nodes
24     num_nodes = int((end_x - start_x) / dx) + 1
25     x = np.linspace(start_x, end_x, num_nodes)
26
27     # The CFL condition for diffusion is more restrictive
28     # as for initial condition u = sin(2pi x), max|u| = 1
29     # Pick C_2 = 0.5 to be safe
30     dt = 0.5 * dx**2 / v

```

```
31     num_time_steps = int(np.ceil(t_final / dt))
32     # Adjust dt to fit exactly into t_final
33     dt = t_final / num_time_steps
34
35     u = initial_condition(x)
36
37     # Store history of u for Question 3.4
38     if return_history:
39         t = 0
40         u_history = [deepcopy(u)]
41         times = [t]
42
43     for _ in range(num_time_steps):
44         u = rk4_step(u, dt, dx, v)
45         if return_history:
46             t += dt
47             u_history.append(deepcopy(u))
48             times.append(t)
49
50     if return_history:
51         return x, u, np.array(times), np.array(u_history)
52
53     return x, u
54
55 if __name__ == "__main__":
56     dx = 1e-1
57     t_final = 1
58     x, u = burgers_rk4(dx, t_final)
59
60     # <Some matplotlib styling and enable LaTeX>
61
62     plt.plot(x, u, label=f'$u(x, {t_final})$')
63     plt.title("1D Burgers' Equation with RK4")
64     plt.xlabel("$x$")
65     plt.legend()
66     plt.savefig('./outputs_3/burgers_rk4.png', dpi=300)
67     plt.show()
```

The resulting plot at $T = 1$ second was:



Question 3.3

Compute $\|u - u_h\|_{L^2}$ with a different refined mesh, and show your spatial convergence in a log-log plot.

Solution. The discrete L^2 norm was used to compute our error:

$$\|u - u_h\|_{L^2} = \sqrt{\Delta x \sum_{i=1}^N (u_i - u_{h,i})^2}$$

Where N is the number of spatial nodes in the coarser mesh, u_i is the exact solution at node i , and $u_{h,i}$ is the numerical solution at node i .

The following code was used to compute the L^2 error and plot spatial convergence:

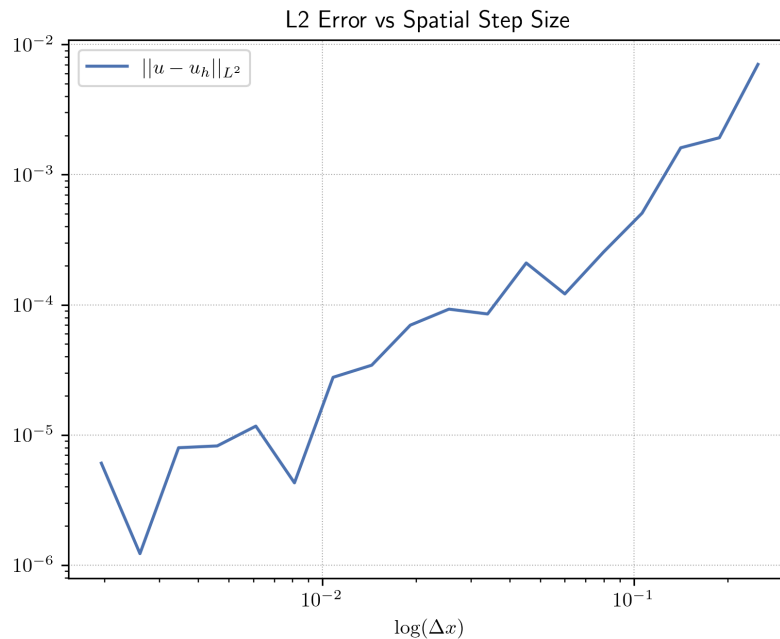
Listing 7: 3.3 Python

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3
4 def discrete_l2(u_num, u_ref, dx):
5     return np.sqrt(np.sum((u_num - u_ref)**2) * dx)
6
7 def spacial_convergence(dx_list, t_final, v=0.2):
8
9     # dx_exact will serve as our "exact" solution
10    # Use a finer dx than minimum dx in dx_list
11    dx_exact = min(dx_list) / 4
12    x_exact, u_exact = burgers_rk4(dx_exact, t_final, v)
13
14    errors = []
15    for dx in dx_list:
16        x_approx, u_approx = burgers_rk4(dx, t_final, v)
17        # Interpolate exact solution to the current mesh of x_approx
18        u_exact_on_x_approx = np.interp(x_approx, x_exact, u_exact)
19        error = discrete_l2(u_approx, u_exact_on_x_approx, dx)
20        errors.append(error)
21    return dx_list, errors
22
23 if __name__ == "__main__":
24     # <Some matplotlib styling and enable LaTeX>
25     dx_list = np.logspace(-2, -9, 18, base=2)
26     dx, error = spacial_convergence(dx_list, t_final)
27     plt.loglog(dx, error, label='$\|u - u_h\|_{L^2}$')
28     plt.xlabel('$\log(\Delta x)$')
29     plt.title('L2 Error vs Spatial Step Size')
30     plt.legend()
31     plt.savefig('./outputs_3/burgers_rk4_error.png', dpi=300)
32     plt.show()

```

The plot generated for spatial convergence at $T = 1$ was:



A few notes:

1. $\Delta x = \frac{1}{2}$ has been excluded from the plot as it had favorable error due to the coarse mesh aligning well with the sine wave at $T = 1$.
2. The fluctuations in the error can be explained by additional interpolation error when mapping the exact solution to the coarser mesh and/or point 1 above.

Overall, we observe second-order spatial convergence as Δx decreases.

Question 3.4

Plot your $\|u - u_h\|_{L^2}$ vs time.

Solution. The following code was used to compute and plot the L^2 error vs time:

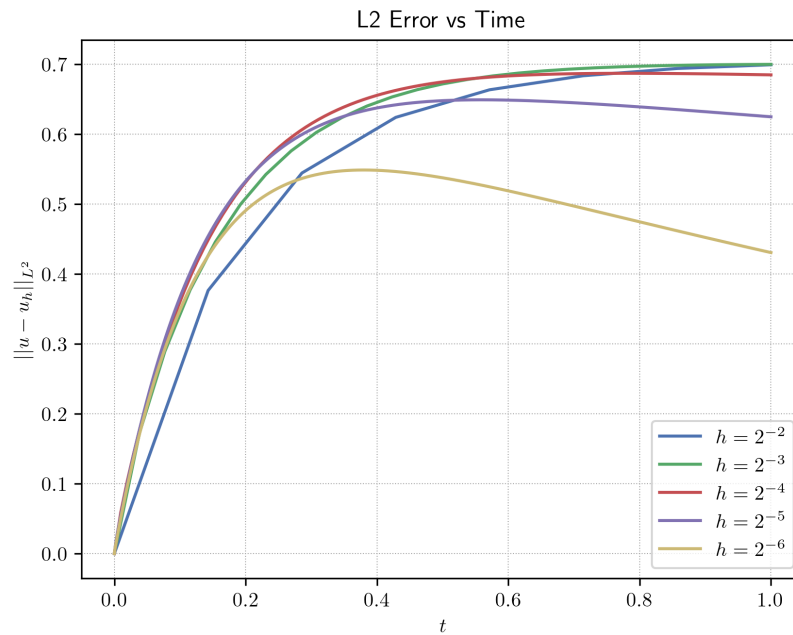
Listing 8: 3.4 Python

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3
4 def norm_vs_time(dx, t_final, x_exact, u_exact_history, v=0.2):
5     x_approx, _, times, u_history = burgers_rk4(dx, t_final, v, return_history=
6     True)
7
8     norms = []
9     for u_approx, u_exact in zip(u_history, u_exact_history):
10         u_exact_on_x_approx = np.interp(x_approx, x_exact, u_exact)
11         norm = discrete_l2(u_approx, u_exact_on_x_approx, dx)
12         norms.append(norm)
13     return times, norms
14
15 if __name__ == "__main__":
16     # <Some matplotlib styling and enable LaTeX>
17     dx_list = np.logspace(-2, -6, 5, base=2)
18
19     dx_exact = min(dx_list) / 4
20     x_exact, _, _, u_exact_history = burgers_rk4(dx_exact, t_final,
21     return_history=True)
22
23     for index, dx in enumerate(dx_list):
24         time, norms = norm_vs_time(dx, t_final, x_exact, u_exact_history)
25         plt.plot(time, norms, label=f'$h = 2^{{{-index-2}}}$')
26     plt.xlabel('$t$')
27     plt.ylabel(r'$\|u - u_h\|_{L^2}$')
28     plt.title('L2 Error vs Time')
29     plt.legend()
30     plt.savefig('./outputs_3/burgers_rk4_error_vs_time.png', dpi=300)
31     plt.show()

```


The plot generated for L^2 error vs time was:



We can see that the L^2 error generally increases with time and then stabilizes. The increase makes sense as numerical errors accumulate over time steps.

Finer meshes (smaller h) consistently yield lower errors throughout the simulation at $T = 1$.

Appendix

The complete code used for this assignment is provided in the appendix for reference. Files can be accessed directly at this [GitHub repository](#).

Listing 9: question_1.py

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3
4 def f(x):
5     return 1 / (1 + 25 * x**2)
6
7
8 def f_prime(x):
9     return -50 * x / (1 + 25 * x**2) ** 2
10
11
12 def h_1(x):
13     return (-625 / 338) * x**3 - (475 / 169) * x**2 + 1
14
15
16 def h_2(x):
17     return (625 / 338) * x**3 - (475 / 169) * x**2 + 1
18
19
20 def hermite_coefficients(nodes, f=f, f_prime=f_prime):
21     # Parameterize nodes for Hermite interpolation
22     z = np.concatenate((nodes, nodes))
23     sorted_indexes = z.argsort()
24     z = z[sorted_indexes]
25     num_nodes = len(z)
26
27     # Set up dd table with zeroth dd
28     dd_table = np.array([[f(zi) for zi in z]])
29
30     # First divided difference
31     f_prime_nodes = np.array([f_prime(xi) for xi in nodes])
32     zeros = np.zeros(len(nodes))
33     first_dd = np.concatenate((f_prime_nodes, zeros))[sorted_indexes]
34     for j in range(num_nodes - 1):
35         if j % 2 == 1:
36             first_dd[j] = (dd_table[0, j + 1] - dd_table[0, j]) / (z[j + 1] - z[j])
37     dd_table = np.vstack([dd_table, first_dd])
38
39     # Remaining Divided Differences
40     for i in range(2, num_nodes):

```

```

41     ith_dd = np.zeros(num_nodes)
42
43     for j in range(num_nodes - i):
44         # Calculate ith divided differences
45         ith_dd[j] = (dd_table[i - 1, j + 1] - dd_table[i - 1, j]) / (
46             z[j + i] - z[j]
47         )
48
49     dd_table = np.vstack([dd_table, ith_dd])
50
51     coefficients = np.array([dd_table[i, 0] for i in range(dd_table.shape[0])])
52     return coefficients, dd_table.T, z
53
54
55 def generate_hermite(nodes, n):
56     # Get coefficients
57     a = hermite_coefficients(nodes)[0]
58     # Start with function and constant term
59     equation = f"P_{{{2 * n + 1}}}(x) = {a[0]}"
60     w = []
61     # Build (x - xi) terms
62     for xi in nodes:
63         if abs(xi) <= 1e-14:
64             w.append("(x)")
65         elif xi < 0:
66             w.append(f"(x + {abs(xi)})")
67         else:
68             w.append(f"(x - {xi})")
69     b = ""
70
71     # Build polynomial string
72     for i in range(1, len(a)):
73         for j in range(i):
74             # Multiply (x - xi) terms
75             b += "^2" if j % 2 == 1 else w[int(j / 2)]
76             # Multiply (x - xi) product with current coefficient and add term
77             if a[i] > 0:
78                 equation += f" + {a[i]}{b}"
79             elif a[i] < 0:
80                 equation += f" - {abs(a[i])}{b}"
81         b = ""
82
83     return equation
84
85
86 def calculate_hermite(nodes, x_coords=[], function=f):
87     # Get coefficients

```

```

88     a, z = hermite_coefficients(nodes, function)[:3:2]
89     # If no x_coords provided, use nodes as x_coords
90     if len(x_coords) == 0:
91         x_coords = nodes
92     # Start with constant term
93     y = a[0]
94     # Build (x - zi) terms
95     w = [(x_coords - zi) for zi in z]
96     # Temporary variable to hold (x - zi) product
97     b = 1
98     for i in range(1, len(a)):
99         for j in range(i):
100             # Multiply (x - zi) terms
101             b *= w[j]
102             # Multiply (x - zi) product with current coefficient
103             y += a[i] * b
104             b = 1
105
106     return y
107
108
109 if __name__ == "__main__":
110     nodes_1 = np.array([-1, 0])
111     equation_1 = generate_hermite(nodes_1, 1)
112     table_1, z_1 = hermite_coefficients(nodes_1)[1:3]
113
114     nodes_2 = np.array([0, 1])
115     equation_2 = generate_hermite(nodes_2, 1)
116     table_2, z_2 = hermite_coefficients(nodes_2)[1:3]
117
118     equations = [equation_1, equation_2]
119     tables = [table_1, table_2]
120     z = [z_1, z_2]
121
122     with open("./outputs_3/hermite.txt", "w") as file:
123         for k in range(2):
124             file.write(equations[k] + "\n\n")
125
126             file.write("\\begin{center}\\n")
127             file.write("\\begin{tabular}{|c|c|c|c|c|}\\n")
128             file.write("\\hline\\n")
129             file.write("& $z_i$ & $f[z_i]$ & 1st dd. & 2nd dd. & 3rd dd. \\\\\\n")
130
131             file.write("\\hline\\n")
132             for i in range(tables[k].shape[0]):
133                 file.write(f"$z_{i}$ & ${z[k][i]}$ ")
134                 for j in range(tables[k].shape[1]):

```

```

134         file.write(f"& ${tables[k][i, j]:.4f}$ ")
135     file.write("\\\\ \n")
136     file.write("\\hline\n")
137     file.write("\\end{tabular}\n")
138     file.write("\\end{center}\n\n")
139
140     plt.rcParams["text.usetex"] = True
141     plt.rcParams["axes.grid"] = True
142     plt.rc("grid", color="#a6a6a6", linestyle="dotted", linewidth=0.5)
143     plt.style.use("seaborn-v0_8-deep")
144     prop_cycle = plt.rcParams["axes.prop_cycle"]
145     default_colors = prop_cycle.by_key()["color"]
146
147     x = np.linspace(-1, 1, 200)
148     f_y = f(x)
149
150     conditions = [x <= 0, x > 0]
151     h_y = np.piecewise(x, conditions, [h_1, h_2])
152     p_y = np.concatenate(
153         (calculate_hermite(nodes_1, x[:100]), calculate_hermite(nodes_2, x
154         [100:]))
155     )
156
157     plt.plot(x, f_y, label="$f(x)$")
158     plt.plot(x, h_y, label="$H(x)$")
159     plt.xlabel("$x$")
160     plt.ylabel("$y$")
161     plt.legend()
162     plt.title("Function and Cubic Hermite")
163     plt.savefig("./outputs_3/hermite_plot_h.png", dpi=300)
164     plt.cla()
165
166     plt.plot(x, f_y, label="$f(x)$")
167     plt.plot(x, p_y, label="$P(x)$", color = default_colors[2])
168     plt.xlabel("$x$")
169     plt.ylabel("$y$")
170     plt.legend()
171     plt.title("Function and Cubic Hermite (Newton Form)")
172     plt.savefig("./outputs_3/hermite_plot_p.png", dpi=300)
173     plt.cla()
174
175     plt.plot(x, f_y, label="$f(x)$")
176     plt.plot(x, h_y, label="$H(x)$")
177     plt.plot(x, p_y, label="$P(x)$")
178     plt.xlabel("$x$")
179     plt.ylabel("$y$")
180     plt.legend()

```

```

180 plt.title("Function and Cubic Hermite Interpolations")
181 plt.savefig("./outputs_3/hermite_plot.png", dpi=300)

```

Listing 10: question_2.py

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3
4 def forward_diff(f, x, step=1):
5     return (f(x + step) - f(x)) / step
6
7 def three_point_forward_diff(f, x, step=1):
8     return (-3 * f(x) + 4 * f(x + step) - f(x + 2 * step)) / (2 * step)
9
10 def calc_absolute_error(f, step, eval_x=1, diff_method=forward_diff):
11     approx = diff_method(f, eval_x, step)
12     return np.abs(approx - f(eval_x))
13
14 if __name__ == "__main__":
15     with open("./outputs_3/forward_diff.txt", "w") as file:
16         for k in range(1,11):
17             h = 10**(-k)
18             f_prime = forward_diff(np.exp, 1.5, h)
19             file.write(f'\\[D_h^{{{k}}}]f(1.5) = {f_prime}\\[\\n')
20
21     plt.rcParams["text.usetex"] = True
22     plt.rcParams["axes.grid"] = True
23     plt.rc("grid", color="#a6a6a6", linestyle="dotted", linewidth=0.5)
24     plt.style.use("seaborn-v0_8-deep")
25
26     h = np.logspace(-1, -10, 200)
27     error = calc_absolute_error(np.exp, h)
28
29     plt.loglog(h, error, label='$\\log|D_{hf}(1) - f\'(1)|$')
30     plt.xlabel('$\\log(h)$')
31     plt.title('Absolute Error with Forward Difference')
32     plt.legend()
33     plt.savefig('./outputs_3/forward_diff_graph.png', dpi=300)
34     plt.show()
35
36     with open("./outputs_3/three_point_forward_diff.txt", "w") as file:
37         for k in range(1,11):
38             h = 10**(-k)
39             f_prime = three_point_forward_diff(np.exp, 1.5, h)
40             file.write(f'\\[D_h^{{{k}}}]f(1.5) = {f_prime}\\[\\n')
41
42     h = np.logspace(-1, -10, 200)
43     error = calc_absolute_error(np.exp, h, diff_method=three_point_forward_diff

```

```

)

44
45 plt.loglog(h, error, label='$\\log|D_{hf}(1) - f\\'(1)|$')
46 plt.xlabel('$\\log(h)$')
47 plt.title('Absolute Error with Three Point Forward Difference')
48 plt.legend()
49 plt.savefig('./outputs_3/three_point_forward_diff_graph.png', dpi=300)
50 plt.show()

```

Listing 11: question_3.py

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3 from copy import deepcopy
4
5 def initial_condition(x):
6     return np.sin(2 * np.pi * x)
7
8 def rk4_step(u, dt, dx, v):
9     def F(u):
10         # Compute spatial derivatives using central differences
11         u_x = (np.roll(u, -1) - np.roll(u, 1)) / (2 * dx)
12         u_xx = (np.roll(u, -1) - 2 * u + np.roll(u, 1)) / (dx**2)
13         return -u * u_x + v * u_xx
14
15     k1 = F(u)
16     k2 = F(u + 0.5 * dt * k1)
17     k3 = F(u + 0.5 * dt * k2)
18     k4 = F(u + dt * k3)
19
20     return u + (dt / 6) * (k1 + 2 * k2 + 2 * k3 + k4)
21
22 def burgers_rk4(dx, t_final, v=0.2, start_x=0, end_x=1, return_history=False):
23     # Take ceil for num_nodes
24     num_nodes = int((end_x - start_x) / dx) + 1
25     x = np.linspace(start_x, end_x, num_nodes)
26
27     # The CFL condition for diffusion is more restrictive
28     # as for initial condition u = sin(2pi x), max|u| = 1
29     # Pick C_2 = 0.5 to be safe
30     dt = 0.5 * dx**2 / v
31     num_time_steps = int(np.ceil(t_final / dt))
32     # Adjust dt to fit exactly into t_final
33     dt = t_final / num_time_steps
34
35     u = initial_condition(x)
36
37     # Store history of u for Question 3.4

```

```

38     if return_history:
39         t = 0
40         u_history = [deepcopy(u)]
41         times = [t]
42
43     for _ in range(num_time_steps):
44         u = rk4_step(u, dt, dx, v)
45         if return_history:
46             t += dt
47             u_history.append(deepcopy(u))
48             times.append(t)
49
50     if return_history:
51         return x, u, np.array(times), np.array(u_history)
52
53     return x, u
54
55 def discrete_l2(u_num, u_ref, dx):
56     return np.sqrt(np.sum((u_num - u_ref)**2) * dx)
57
58 def spacial_convergence(dx_list, t_final, v=0.2):
59
60     # dx_exact will serve as our "exact" solution
61     # Use a finer dx than minimum dx in dx_list
62     dx_exact = min(dx_list) / 4
63     x_exact, u_exact = burgers_rk4(dx_exact, t_final, v)
64
65     errors = []
66     for dx in dx_list:
67         x_approx, u_approx = burgers_rk4(dx, t_final, v)
68         # Interpolate exact solution to the current mesh of x_approx
69         u_exact_on_x_approx = np.interp(x_approx, x_exact, u_exact)
70         error = discrete_l2(u_approx, u_exact_on_x_approx, dx)
71         errors.append(error)
72     return dx_list, errors
73
74 def norm_vs_time(dx, t_final, x_exact, u_exact_history, v=0.2):
75     x_approx, _, times, u_history = burgers_rk4(dx, t_final, v, return_history=
True)
76
77     norms = []
78     for u_approx, u_exact in zip(u_history, u_exact_history):
79         u_exact_on_x_approx = np.interp(x_approx, x_exact, u_exact)
80         norm = discrete_l2(u_approx, u_exact_on_x_approx, dx)
81         norms.append(norm)
82     return times, norms
83

```



```

84 if __name__ == "__main__":
85     dx = 1e-2
86     t_final = 1
87     x, u = burgers_rk4(dx, t_final)
88
89     plt.rcParams["text.usetex"] = True
90     plt.rcParams["axes.grid"] = True
91     plt.rc("grid", color="#a6a6a6", linestyle="dotted", linewidth=0.5)
92     plt.style.use("seaborn-v0_8-deep")
93
94     plt.plot(x, u, label=f'$u(x, {t_final})$')
95     plt.title("1D Burgers' Equation with RK4")
96     plt.xlabel("$x$")
97     plt.legend()
98     plt.savefig('./outputs_3/burgers_rk4.png', dpi=300)
99     plt.cla()
100
101     dx_list = np.logspace(-2, -9, 18, base=2)
102     dx, error = spacial_convergence(dx_list, t_final)
103     plt.loglog(dx, error, label='$||u - u_h||_{L^2}$')
104     plt.xlabel('$\\log(\\Delta x)$')
105     plt.title('L2 Error vs Spatial Step Size')
106     plt.legend()
107     plt.savefig('./outputs_3/burgers_rk4_error.png', dpi=300)
108     plt.show()
109
110     dx_list = np.logspace(-2, -6, 5, base=2)
111
112     dx_exact = min(dx_list) / 4
113     x_exact, _, _, u_exact_history = burgers_rk4(dx_exact, t_final,
114     return_history=True)
115
116     for index, dx in enumerate(dx_list):
117         time, norms = norm_vs_time(dx, t_final, x_exact, u_exact_history)
118         plt.plot(time, norms, label=f'$h = 2^{{{index-2}}}$')
119     plt.xlabel('$t$')
120     plt.ylabel(r'$||u - u_h||_{L^2}$')
121     plt.title('L2 Error vs Time')
122     plt.legend()
123     plt.savefig('./outputs_3/burgers_rk4_error_vs_time.png', dpi=300)
124     plt.show()

```