

ECSE 543

Assignment 3

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Introduction

The code for this assignment was created in Python 2.7 and can be seen in Appendix A. To perform the required tasks in this assignment, the `Matrix` class from Assignment 1 was used, with useful methods such as `add`, `multiply`, `transpose`, etc. This package can be seen in the `matrices.py` file shown in Listing 1. The only packages used that are not built-in are those for creating the plots for this report, i.e., `matplotlib` for plotting. The structure of the rest of the code will be discussed as appropriate for each question. Output logs of the program are provided in Appendix B.

1 BH Interpolation

The source code for the Question 1 program can be seen in the `q1.py` file shown in Listing 2.

1.a Lagrange Polynomials

To interpolate $n = 6$ points of a function $y(x)$, six 5th-order Lagrange polynomials are needed. Each of these polynomials L_j is given by Equation (1), where each F_j is given by Equation (2).

$$L_j(x) = \frac{F_j(x)}{F_j(x_j)} \quad (1)$$

$$F_j(x) = \prod_{r=1, \dots, n, r \neq j} (x - x_r) \quad (2)$$

The interpolation $\tilde{y}(x)$ of $y(x)$ is then given by Equation (3).

$$\tilde{y}(x) = \sum_{j=1}^n y(x_j) L_j(x) \quad (3)$$

To ease the handling of these polynomials, a `Polynomial` class was created, with useful methods like `add`, `multiply` and `evaluate`. This class can be found in the `polynomial.py` file shown in Listing 3 and the associated tests can be found in the `polynomial.test.py` file shown in Listing 4.

The code evaluating the polynomials in Equations (1) to (3) for interpolation can be found in the `lagrange.py` file shown in Listing 5. The associated tests are in the `test_lagrange.py` file shown in Listing 6.

The interpolation for the first 6 points of the B - H curve is evaluated in `q1.py` shown in Listing 2, with output logged in Listing 19. The generated plot can be seen in Figure 1. It can be seen that the interpolation passes through all the data points, as expected. The curve is also relatively smooth, and

should be a good approximation of the B - H curve over that range.

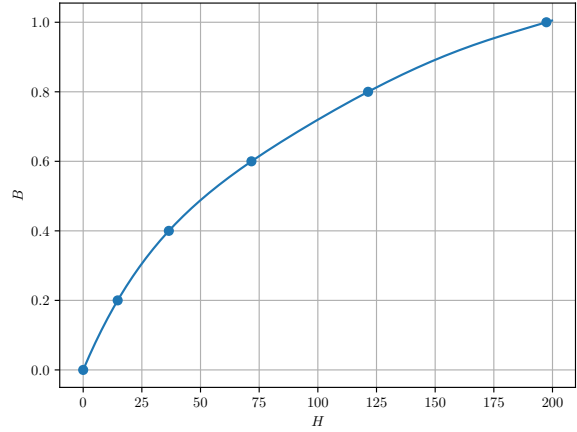


Figure 1: Lagrange interpolation of the first 6 points ($B = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0$) in the B - H curve. The points are from the table and the curve is interpolated.

1.b Full-Domain Interpolation

The interpolation for the given six points is computed in `q1.py` shown in Listing 2 with output in Listing 19. The generated plot can be seen in Figure 2. The curve passes through all the given points, but is clearly not plausible. It has the characteristic “wiggles” seen when using full-domain Lagrange polynomials over a wide range. It even shows negative B values, which do not match the actual values in between the chosen points.

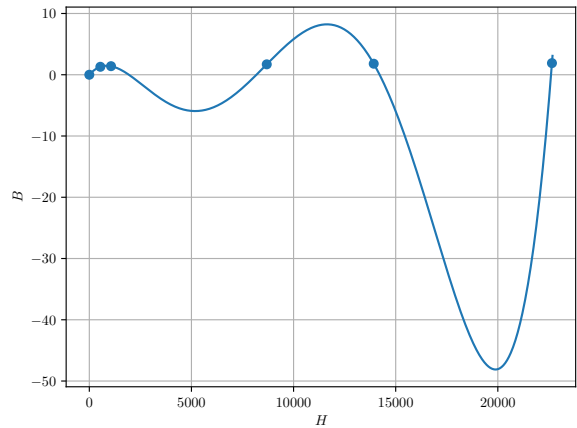


Figure 2: Lagrange interpolation of 6 points ($B = 0.0, 1.3, 1.4, 1.7, 1.8, 1.9$) in the B - H curve. The points are from the table and the curve is interpolated.

1.c Cubic Hermite Polynomials

The slopes at each of the 6 points can be approximated by the slope of the straight line passing through the two adjacent points, i.e., the point immediately before and the point after the point of interest. For the boundary points of 0 T and 1.9 T, the slope of the line formed by the boundary point itself and one adjacent point can be used.

2 Magnetic Circuit

The source code for the Question 2 program can be seen in the `q2.py` file shown in Listing 7.

2.a Flux Equation

The magnetic analog of KVL can be seen in Equation (4).

$$(\mathcal{R}_a + \mathcal{R}_c)\psi = \mathcal{F} \quad (4)$$

where \mathcal{R}_a is the reluctance of the air gap, \mathcal{R}_c is the reluctance of the coil, and \mathcal{F} is the magnetomotive force. Plugging in the relevant variables from the problem, we obtain Equation (5).

$$\left(\frac{L_a}{A\mu_o} + \frac{L_c}{A\mu_c(\psi)} \right) \psi - NI = 0 \quad (5)$$

where $\mu_c(\psi)$ is a function of ψ given by Equation (6).

$$\mu_c(\psi) = \frac{B(\psi)}{H(\psi)} = \frac{\psi}{AH(\psi)} \quad (6)$$

Plugging Equation (6) into Equation (5), we obtain Equation (7).

$$\left(\frac{L_a}{A\mu_o} + \frac{L_c H(\psi)}{\psi} \right) \psi - NI = 0 \quad (7)$$

Simplifying the terms, we obtain Equation (8).

$$f(\psi) = \frac{L_a \psi}{A\mu_o} + L_c H(\psi) - NI = 0 \quad (8)$$

Finally, if we plug in the values from the question, we obtain Equation (9), where the coefficients of the terms are calculated in the `q2.py` script shown in Listing 2.

$$f(\psi) = 3.979 \times 10^7 \psi + 0.3H(\psi) - 8000 = 0 \quad (9)$$

In Equation (9), $H(\psi)$ can be calculated for a given ψ by first finding $B = \psi/A$, and then using the B - H curve to find H .

2.b Newton-Raphson

To perform the Newton-Raphson update, the derivative f' of f will be needed. This can be seen in Equation (10), where the $1/A$ term comes from the fact that $B(\psi) = \psi/A$ and $H(\psi) = H(B(\psi)) = H(\psi/A)$.

$$\begin{aligned} f'(\psi) &= 3.979 \times 10^7 + \frac{0.3H'(\psi)}{A} \\ &= 3.979 \times 10^7 + 3000H' \end{aligned} \quad (10)$$

In Equation (10), the derivative H' of H can be estimated using the slope between each of the points given in the B - H table of Question 1. The slope interpolation code is in the `slope_interpolation.py` script shown in Listing 10.

A piecewise-linear interpolation of the data in the B - H table is also needed. This can easily be obtained using the Lagrange polynomial program created for Question 1. Here, we simply need to interpolate 2 points in every sub-domain using 1st-order Lagrange polynomials. We will also need to interpolate H as a function of B to evaluate Equation (9), unlike in Question 1. The linear interpolation code is in the `piecewise_linear.py` script shown in Listing 9. The generated piecewise-linear interpolation fits the B - H points, as can be seen in Figure 3.

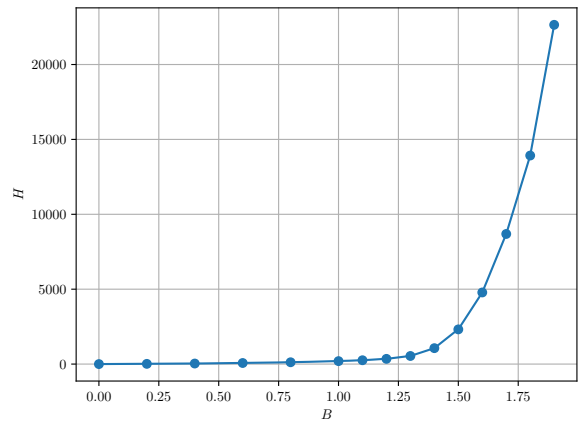


Figure 3: Piecewise-linear interpolation of the H - B curve.

With f given by Equation (9) and f' given by Equation (10), the Newton-Raphson update equation for the flux ψ is given by Equation (11).

$$\psi^{(k+1)} \leftarrow \psi^{(k)} - \frac{f(\psi^{(k)})}{f'(\psi^{(k)})} \quad (11)$$

The code performing the Newton-Raphson update is in `newton_raphson.py` and can be seen in

Listing 8. The executing program is in `q2.py` shown in Listing 7, with associated output in Listing 20. The program takes 3 steps to solve for a flux of approximately $\psi = 1.613 \times 10^{-4}$ Wb.

2.c Successive Substitution

First, the Newton-Raphson update equation in Equation (11) was simply adjusted to set $f' = 1$, as shown in Equation (12).

$$\psi^{(k+1)} \leftarrow \psi^{(k)} - f^{(k)} \quad (12)$$

However, this method did not converge. Then, inspired from the fact that one must typically use the natural logarithm to solve exponential equations with successive substitution, the update equation was changed to use the inverse of the $H(B(\psi))$ function. Note that when taking the inverse, one must multiply the expression by the cross-sectional area $A = 1 \times 10^{-4}$ m², since $B(\psi) = \psi/A$. This update equation can be seen in Equation (13), where the inverse H function is denoted as H^{-1} .

$$\psi^{(k+1)} \leftarrow AH^{-1} \left(\frac{NI - \frac{L_a}{A\mu_o}\psi^{(k)}}{L_c} \right) \quad (13)$$

The update equation with all the plugged in values can be seen in Equation (14).

$$\psi^{(k+1)} \leftarrow 1 \times 10^{-4} H^{-1} \left(\frac{8000 - 3.98 \times 10^7 \psi^{(k)}}{0.3} \right) \quad (14)$$

The code evaluating the inverse function H^{-1} is in the `piecewise_linear_inverse.py` script shown in Listing 12. The successive substitution code is in the `successive_substitution.py` script shown in Listing 11. The executing program is in the `q2.py` file shown in Listing 7 with output in Listing 20. The method converges to the same value of $\psi = 1.613 \times 10^{-4}$ Wb as Newton-Raphson, but in 15 steps instead of 3.

3 Diode Circuit

The source code for the Question 3 program can be seen in the `q3.py` file shown in Listing 15.

3.a Voltage Equations

The current-voltage relationship for a diode is given by Equation (15).

$$I = I_s \left(\exp \left[\frac{qv}{kT} \right] - 1 \right) \quad (15)$$

Let the nodal voltage at the anode of the A diode be denoted by v_A and that of the B diode by v_B . Let the current through the circuit be denoted by I . The diode equations for A and B can be seen in Equations (16) and (17).

$$I = I_{sA} \left(\exp \left[\frac{q(v_A - v_B)}{kT} \right] - 1 \right) \quad (16)$$

$$I = I_{sB} \left(\exp \left[\frac{qv_B}{kT} \right] - 1 \right) \quad (17)$$

By KVL, we also have Equation (18), relating V_A and I .

$$I = \frac{E - v_A}{R} \quad (18)$$

Equating Equations (16) and (18), we obtain the nonlinear equation for v_A , shown in Equation (19).

$$\begin{aligned} f_A(v_A, v_B) &= v_A + RI_{sA} \left(\exp \left[\frac{q(v_A - v_B)}{kT} \right] - 1 \right) - E \\ &= 0 \end{aligned} \quad (19)$$

Equating Equations (16) and (17), we obtain the nonlinear equation for v_B , shown in Equation (20).

$$\begin{aligned} f_B(v_A, v_B) &= I_{sA} \left(\exp \left[\frac{q(v_A - v_B)}{kT} \right] - 1 \right) \\ &\quad - I_{sB} \left(\exp \left[\frac{qv_B}{kT} \right] - 1 \right) = 0 \end{aligned} \quad (20)$$

The total system of equations can then be expressed by Equation (21).

$$\mathbf{f}(\mathbf{v}_n) = \begin{bmatrix} f_A(v_A, v_B) \\ f_B(v_A, v_B) \end{bmatrix} = \mathbf{0} \quad (21)$$

3.b Newton-Raphson

To find an expression for the Jacobian matrix \mathbf{F} , we must first find expressions for all the partials of f_A and f_B . These are shown in Equations (22) to (25).

$$\frac{\partial f_A}{\partial v_A} = 1 + RI_{sA} \left(\exp \left[\frac{q(v_A - v_B)}{kT} \right] \frac{q}{kT} \right) \quad (22)$$

$$\frac{\partial f_A}{\partial v_B} = -RI_{sA} \left(\exp \left[\frac{q(v_A - v_B)}{kT} \right] \frac{q}{kT} \right) \quad (23)$$

$$\frac{\partial f_B}{\partial v_A} = I_{sA} \left(\exp \left[\frac{q(v_A - v_B)}{kT} \right] \frac{q}{kT} \right) \quad (24)$$

$$\begin{aligned} \frac{\partial f_B}{\partial v_B} = & -I_{sA} \left(\exp \left[\frac{q(v_A - v_B)}{kT} \right] \frac{q}{kT} \right) \\ & - I_{sB} \left(\exp \left[\frac{qv_B}{kT} \right] \frac{q}{kT} \right) \end{aligned} \quad (25)$$

With these equations, the Jacobian matrix \mathbf{F} is given by Equation (26).

$$\mathbf{F} = \begin{bmatrix} \frac{\partial f_A}{\partial v_A} & \frac{\partial f_A}{\partial v_B} \\ \frac{\partial f_B}{\partial v_A} & \frac{\partial f_B}{\partial v_B} \end{bmatrix} \quad (26)$$

With this information, we can apply the Newton-Raphson update in matrix form, shown in Equation (27).

$$\mathbf{v}_n^{(k+1)} \leftarrow \mathbf{v}_n^{(k)} - (\mathbf{F}^{(k)})^{-1} \mathbf{f}^{(k)} \quad (27)$$

The code performing this update is in the `newton_raphson_matrix.py` script and can be seen in Listing 16. The initial guess is $v_A = 0\text{V}$ and $v_B = 0\text{V}$. The program terminates when $\|\mathbf{f}\|/\|\mathbf{f}_0\|$ is less than some ϵ , as shown in Equation (28). The chosen value of ϵ is 1×10^{-9} . To calculate the norm, the 2-norm, i.e., the Euclidean norm, of the vectors is used.

$$\text{Error} = \frac{\|\mathbf{f}\|}{\|\mathbf{f}_0\|} < \epsilon \quad (28)$$

The code is executed in the `q3.py` script shown in Listing 15, with output shown in Listing 21. The final solved voltage values are 198.134 mV for v_A and 90.571 mV for v_B . The recorded values of v_A , v_B , f_A and f_B at each step can be seen in Table 1.

Table 1: Node voltages and \mathbf{f} values at every iteration of Newton-Raphson.

v_A (mV)	v_B (mV)	f_A	f_B
0.000	0.000	-2.200×10^{-1}	0.000
218.254	72.751	9.906×10^{-2}	1.808×10^{-4}
205.695	81.581	2.837×10^{-2}	5.519×10^{-5}
200.110	89.250	5.100×10^{-3}	8.561×10^{-6}
198.211	90.516	1.943×10^{-4}	3.331×10^{-7}
198.134	90.571	3.088×10^{-7}	5.098×10^{-10}
198.134	90.571	7.538×10^{-13}	1.276×10^{-15}

The error at each step can be seen in Figure 4, where the error expression is given by Equation (28). It can be seen that the convergence is indeed quadratic.

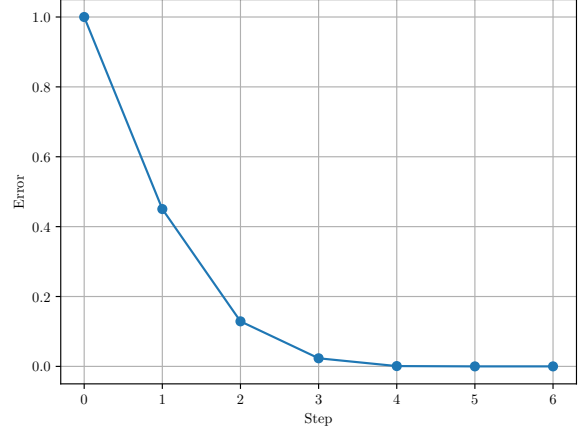


Figure 4: Error at each step of Newton-Raphson to solve the diode circuit. The error equation is given by Equation (28).

4 Function Integration

The source code for the Question 4 program can be seen in the `q4.py` file shown in Listing 17.

4.a Cosine Integration

The integral I to be solved by Gauss-Legendre integration is shown in Equation (29).

$$I = \int_{x_1}^{x_2} f(x) dx \quad (29)$$

To use Gauss-Legendre integration over N equal segments, the $[x_1, x_2]$ range of x must be mapped to N intervals of size h , with each interval i having a center point x_{0_i} , with x_i ranging from $x_{0_i} - h/2$ to $x_{0_i} + h/2$. Each of these intervals must be mapped to a $[-1, 1]$ range for ζ_i . This mapping between x_i and ζ_i over an interval is given by Equation (30).

$$x_i = x_{0_i} + \frac{h}{2} \zeta_i \quad (30)$$

The integral transformation from x to ζ over an interval i is then given by Equation (31).

$$\begin{aligned} I_i &= \int_{x_{0_i} - h/2}^{x_{0_i} + h/2} f(x_i) dx_i \\ &= \frac{h}{2} \int_{-1}^1 f \left[x_{0_i} + \frac{h}{2} \zeta_i \right] d\zeta_i \end{aligned} \quad (31)$$

The one-point Gauss-Legendre approximation can then be applied for each interval, as shown in Equation (32), where $w_0 = 2$.

$$\begin{aligned}
I_i &= \frac{h}{2} \int_{-1}^1 f \left[x_{0_i} + \frac{h}{2} \zeta_i \right] d\zeta_i \\
&= \frac{h}{2} w_0 f(x_{0_i}) \\
&= h f(x_{0_i})
\end{aligned} \tag{32}$$

The equation approximating I is then given by Equation (33).

$$\begin{aligned}
I &\approx \sum_{i=0}^{N-1} I_i \\
&= \sum_{i=0}^{N-1} h f(x_{0_i}) \\
&= h \sum_{i=0}^{N-1} f(x_{0_i})
\end{aligned} \tag{33}$$

To summarize, to solve an integral of the form shown in Equation (29) with one-point Gauss-Legendre integration over N intervals, we simply need the width h of each interval and the value $f(x_{0_i})$ of the function f at the midpoint of every interval.

In the context of this question, $x_1 = 0$ and $x_2 = 1$. The width of each interval is $h = 1/N$ and the midpoint of each interval is $x_{0_i} = 1/(2N) + i/N$. This yields the equation shown in Equation (34).

$$\begin{aligned}
I &= \int_0^1 f(x) dx \\
&\approx \frac{1}{N} \sum_{i=0}^{N-1} f \left[\frac{1}{N} \left(i + \frac{1}{2} \right) \right]
\end{aligned} \tag{34}$$

The code executing Equation (34) for arbitrary $f(x)$ can be seen in the `gauss_legendre.py` script shown in Listing 18.

If we use the fact that $f(x) = \cos x$ as well for this question, we obtain Equation (35).

$$I \approx \frac{1}{N} \sum_{i=0}^{N-1} \cos \left[\frac{1}{N} \left(i + \frac{1}{2} \right) \right] \tag{35}$$

To evaluate the estimation, it can be compared to actual value of the integral, which is given by Equation (36).

$$\int_0^1 \cos x dx = \sin 1 - \sin 0 = \sin 1 \approx 0.841 \tag{36}$$

The equation for the absolute error used is shown in Equation (37), where I_{actual} is the actual value of the integral, and I_{approx} is the approximate value computed by Gauss-Legendre integration.

$$E = |I_{actual} - I_{approx}| \tag{37}$$

The integral of $\cos x$ is computed in the `q4.py` script shown in Listing 17, with output shown in Listing 22. The logarithmic plot of the error versus N can be seen in Figure 5. The straight-line slope of the plot is indicative of the fact that first-order Gauss-Legendre integration was used. It can also be seen that there are diminishing returns to using a high value of N .

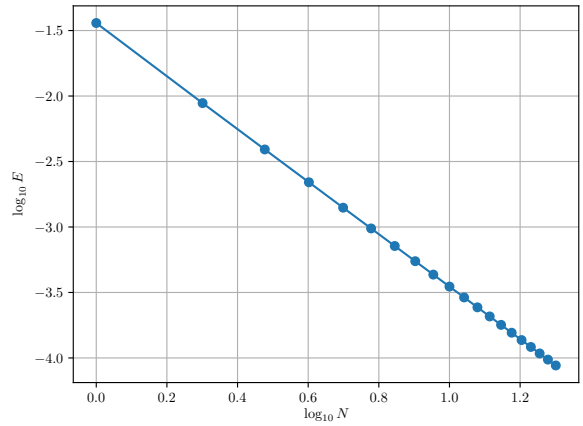


Figure 5: Logarithmic plot of the error E versus number of intervals N for $f(x) = \cos x$.

4.b Log Integration

The integral I to be evaluated is shown in Equation (38).

$$I = \int_0^1 \log_e x dx \tag{38}$$

Using Equation (34) for $f(x) = \log_e x$, we obtain the integral shown in Equation (39).

$$I \approx \frac{1}{N} \sum_{i=0}^{N-1} \log_e \left[\frac{1}{N} \left(i + \frac{1}{2} \right) \right] \tag{39}$$

The actual value of the integral to which the estimation is compared is shown in Equation (40).

$$\int_0^1 \log_e x dx = -1 \tag{40}$$

The integral of $\log_e x$ is computed in the `q4.py` script shown in Listing 17, with output shown in

Listing 22. The logarithmic plot of the error versus N can be seen in Figure 6. Once again, the straight-line slope of the plot is indicative of the fact that first-order Gauss-Legendre integration was used. It can also be seen that there are diminishing returns to using a high value of N .

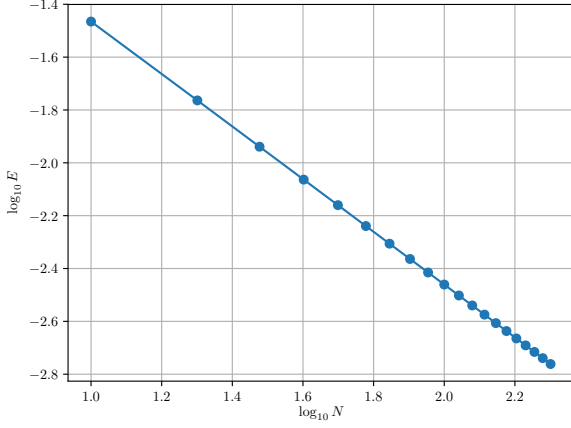


Figure 6: Logarithmic plot of the error E versus number of intervals N for $f(x) = \log_e x$.

4.c Log Integration Improvement

To have arbitrary interval widths, Equation (33) must be adjusted, as shown in Equation (41), where h_i is the width of interval i .

$$I \approx \sum_{i=0}^{N-1} h_i f(x_{0_i}) \quad (41)$$

It is more convenient to adjust relative interval widths to find a suitable combination. The relative widths used are shown in Equation (42).

$$(h_{rel_i})_{i=0}^{N-1} = (1, 2, 3, 4, 5, 6, 7, 8, 9, 10) \quad (42)$$

These relative widths are converted to actual widths and then used to compute the integral in the `gauss_legendre.py` script shown in Listing 18. The code is executed in the `q4.py` script shown in Listing 17, with output shown in Listing 22. How closely the widths approximate the $\log_e x$ curve can be seen in Figure 7. The estimated value of the integral is -0.988377 with absolute error of 0.011622 . This is much more accurate than the equal-segment version in part (b), which obtained a value of -0.965759 and error of 0.034241 .

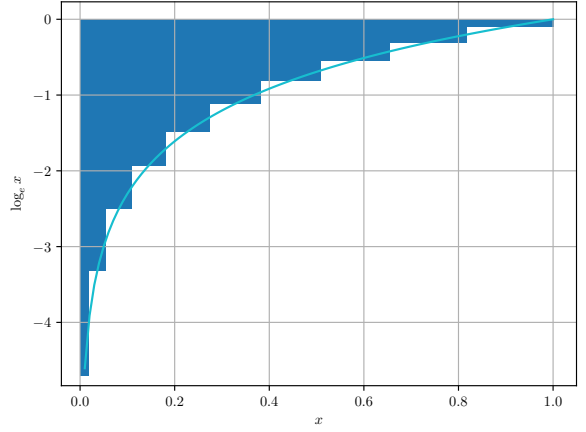


Figure 7: Sizes of intervals used for Question 4(c) in blue, with $\log_e x$ shown as reference in light blue.

A Code Listings

Listing 1: Custom matrix package (*matrices.py*).

```
1  from __future__ import division
2
3  import copy
4  import csv
5  from ast import literal_eval
6
7  import math
8
9
10 class Matrix:
11     def __init__(self, data):
12         self.data = data
13         self.num_rows = len(data)
14         self.num_cols = len(data[0])
15
16     def __str__(self):
17         string = ''
18         for row in self.data:
19             string += '\n'
20             for val in row:
21                 string += '{:6.3f} '.format(val)
22         return string
23
24     def __add__(self, other):
25         if len(self) != len(other) or len(self[0]) != len(other[0]):
26             raise ValueError('Incompatible matrix sizes for addition. Matrix A is {}x{}, but matrix B is
27                 ↳ {}x{}.'.format(len(self), len(self[0]), len(other), len(other[0])))
28
29         return Matrix([[self[row][col] + other[row][col] for col in range(self.num_cols)]
30                        for row in range(self.num_rows)])
31
32     def __sub__(self, other):
33         if len(self) != len(other) or len(self[0]) != len(other[0]):
34             raise ValueError('Incompatible matrix sizes for subtraction. Matrix A is {}x{}, but matrix B
35                 ↳ is {}x{}.'.format(len(self), len(self[0]), len(other), len(other[0])))
36
37         return Matrix([[self[row][col] - other[row][col] for col in range(self.num_cols)]
38                        for row in range(self.num_rows)])
39
40     def __mul__(self, other):
41         if type(other) == float or type(other) == int:
42             return self.scalar_multiply(other)
43
44         if self.num_cols != other.num_rows:
45             raise ValueError('Incompatible matrix sizes for multiplication. Matrix A is {}x{}, but matrix
46                 ↳ B is {}x{}.'.format(self.num_rows, self.num_cols, other.num_rows, other.num_cols))
47
48         # Inspired from https://en.wikipedia.org/wiki/Matrix_multiplication
49         product = Matrix.empty(self.num_rows, other.num_cols)
50         for i in range(self.num_rows):
51             for j in range(other.num_cols):
52                 row_sum = 0
53                 for k in range(self.num_cols):
54                     row_sum += self[i][k] * other[k][j]
55                 product[i][j] = row_sum
56         return product
57
58     def __div__(self, other):
59         """
60         Element-wise division.
61         """
62         if type(other) == float or type(other) == int:
```

```

63         return self.scalar_divide(other)
64
65     if self.num_rows != other.num_rows or self.num_cols != other.num_cols:
66         raise ValueError('Incompatible matrix sizes.')
67     return Matrix([[self[row][col] / other[row][col] for col in range(self.num_cols)]
68                   for row in range(self.num_rows)])
69
70 def __neg__(self):
71     return Matrix([[-self[row][col] for col in range(self.num_cols)] for row in range(self.num_rows)])
72
73 def __deepcopy__(self, memo):
74     return Matrix(copy.deepcopy(self.data))
75
76 def __getitem__(self, item):
77     return self.data[item]
78
79 def __len__(self):
80     return len(self.data)
81
82 @property
83 def transpose(self):
84     """
85     :return: the transpose of the current matrix
86     """
87     return Matrix([[self.data[row][col] for row in range(self.num_rows)] for col in
88                   ↪ range(self.num_cols)])
89
90 @property
91 def infinity_norm(self):
92     if self.num_cols > 1:
93         raise ValueError('Not a column vector.')
94     return max([abs(x) for x in self.transpose[0]])
95
96 @property
97 def two_norm(self):
98     if self.num_cols > 1:
99         raise ValueError('Not a column vector.')
100     return math.sqrt(sum([x ** 2 for x in self.transpose[0]]))
101
102 @property
103 def values(self):
104     """
105     :return: the values in this matrix, in row-major order.
106     """
107     vals = []
108     for row in self.data:
109         for val in row:
110             vals.append(val)
111     return tuple(vals)
112
113 def scaled_values(self, scale):
114     """
115     :return: the values in this matrix, in row-major order.
116     """
117     vals = []
118     for row in self.data:
119         for val in row:
120             vals.append('{:.3f}'.format(val * scale))
121     return tuple(vals)
122
123 @property
124 def item(self):
125     """
126     :return: the single element contained by this matrix, if it is 1x1.
127     """
128     if not (self.num_rows == 1 and self.num_cols == 1):
129         raise ValueError('Matrix is not 1x1')
130     return self.data[0][0]
131
132 def integer_string(self):

```

```

132         string = ''
133         for row in self.data:
134             string += '\n'
135             for val in row:
136                 string += '{:3.0f} '.format(val)
137         return string
138
139     def scalar_multiply(self, scalar):
140         return Matrix([[self[row][col] * scalar for col in range(self.num_cols)] for row in
141             ↪ range(self.num_rows)])
142
143     def scalar_divide(self, scalar):
144         return Matrix([[self[row][col] / scalar for col in range(self.num_cols)] for row in
145             ↪ range(self.num_rows)])
146
147     def is_positive_definite(self):
148         """
149         :return: True if the matrix is positive-definite, False otherwise.
150         """
151         A = copy.deepcopy(self.data)
152         for j in range(self.num_rows):
153             if A[j][j] <= 0:
154                 return False
155             A[j][j] = math.sqrt(A[j][j])
156             for i in range(j + 1, self.num_rows):
157                 A[i][j] = A[i][j] / A[j][j]
158                 for k in range(j + 1, i + 1):
159                     A[i][k] = A[i][k] - A[i][j] * A[k][j]
160         return True
161
162     def mirror_horizontal(self):
163         """
164         :return: the horizontal mirror of the current matrix
165         """
166         return Matrix([[self.data[self.num_rows - row - 1][col] for col in range(self.num_cols)]
167             ↪ for row in range(self.num_rows)])
168
169     def empty_copy(self):
170         """
171         :return: an empty matrix of the same size as the current matrix.
172         """
173         return Matrix.empty(self.num_rows, self.num_cols)
174
175     def save_to_csv(self, filename):
176         """
177         Saves the current matrix to a CSV file.
178
179         :param filename: the name of the CSV file
180         """
181         with open(filename, "wb") as f:
182             writer = csv.writer(f)
183             for row in self.data:
184                 writer.writerow(row)
185
186     def save_to_latex(self, filename):
187         """
188         Saves the current matrix to a latex-readable matrix.
189
190         :param filename: the name of the CSV file
191         """
192         with open(filename, "wb") as f:
193             for row in range(self.num_rows):
194                 for col in range(self.num_cols):
195                     f.write('{} '.format(self.data[row][col]))
196                     if col < self.num_cols - 1:
197                         f.write('& ')
198                 if row < self.num_rows - 1:
199                     f.write('\n')
200
201     @staticmethod

```

```

200 def multiply(*matrices):
201     """
202     Computes the product of the given matrices.
203
204     :param matrices: the matrix objects
205     :return: the product of the given matrices
206     """
207     n = matrices[0].rows
208     product = Matrix.identity(n)
209     for matrix in matrices:
210         product = product * matrix
211     return product
212
213 @staticmethod
214 def empty(num_rows, num_cols):
215     """
216     Returns an empty matrix (filled with zeroes) with the specified number of columns and rows.
217
218     :param num_rows: number of rows
219     :param num_cols: number of columns
220     :return: the empty matrix
221     """
222     return Matrix([[0 for _ in range(num_cols)] for _ in range(num_rows)])
223
224 @staticmethod
225 def identity(n):
226     """
227     Returns the identity matrix of the given size.
228
229     :param n: the size of the identity matrix (number of rows or columns)
230     :return: the identity matrix of size n
231     """
232     return Matrix.diagonal_single_value(1, n)
233
234 @staticmethod
235 def diagonal(values):
236     """
237     Returns a diagonal matrix with the given values along the main diagonal.
238
239     :param values: the values along the main diagonal
240     :return: a diagonal matrix with the given values along the main diagonal
241     """
242     n = len(values)
243     return Matrix([[values[row] if row == col else 0 for col in range(n)] for row in range(n)])
244
245 @staticmethod
246 def diagonal_single_value(value, n):
247     """
248     Returns a diagonal matrix of the given size with the given value along the diagonal.
249
250     :param value: the value of each element on the main diagonal
251     :param n: the size of the matrix
252     :return: a diagonal matrix of the given size with the given value along the diagonal.
253     """
254     return Matrix([[value if row == col else 0 for col in range(n)] for row in range(n)])
255
256 @staticmethod
257 def column_vector(values):
258     """
259     Transforms a row vector into a column vector.
260
261     :param values: the values, one for each row of the column vector
262     :return: the column vector
263     """
264     return Matrix([[value] for value in values])
265
266 @staticmethod
267 def csv_to_matrix(filename):
268     """
269     Reads a CSV file to a matrix.

```

```

270
271     :param filename: the name of the CSV file
272     :return: a matrix containing the values in the CSV file
273     """
274     with open(filename, 'r') as csv_file:
275         reader = csv.reader(csv_file)
276         data = []
277         for row_number, row in enumerate(reader):
278             data.append([literal_eval(val) for val in row])
279     return Matrix(data)

```

Listing 2: Question 1 (q1.py).

```

1  from __future__ import division
2  from lagrange import lagrange_interpolation
3
4  import matplotlib.pyplot as plt
5  from matplotlib import rc
6  rc('font', **{'family': 'serif', 'serif': ['Computer Modern']})
7  rc('text', usetex=True)
8
9  B = [0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9]
10 H = [0.0, 14.7, 36.5, 71.7, 121.4, 197.4, 256.2, 348.7, 540.6, 1062.8, 2317.0, 4781.9, 8687.4, 13924.3,
    ↪ 22650.2]
11
12
13 def q1():
14     print('\n=== Question 1 ===')
15     q1a()
16     q1b()
17
18
19 def q1a():
20     print('\n=== Question 1(a) ===')
21     num_points = 6
22     y_values = B[:num_points]
23     x_values = H[:num_points]
24
25     print('B: {}'.format(y_values))
26     print('H: {}'.format(x_values))
27
28     lagrange_interpolation_polynomial = lagrange_interpolation(x_values, y_values)
29
30     print('Interpolation polynomial: {}'.format(lagrange_interpolation_polynomial))
31
32     plot_polynomial(0, 200, lagrange_interpolation_polynomial, x_values, y_values, filename='q1a')
33
34
35 def q1b():
36     print('\n=== Question 1(b) ===')
37     y_values = [0.0, 1.3, 1.4, 1.7, 1.8, 1.9]
38     x_values = [H[B.index(b)] for b in y_values]
39
40     print('B: {}'.format(y_values))
41     print('H: {}'.format(x_values))
42
43     lagrange_interpolation_polynomial = lagrange_interpolation(x_values, y_values)
44
45     print('Interpolation polynomial: {}'.format(lagrange_interpolation_polynomial))
46
47     plot_polynomial(0, 22700, lagrange_interpolation_polynomial, x_values, y_values, filename='q1b')
48
49
50 def plot_polynomial(x_min, x_max, polynomial, data_x_points, data_y_points, num_points=1000,
    ↪ filename='q1a'):
51     subdivision = (x_max - x_min) / num_points
52     x_range = [x_min + i * subdivision for i in range(num_points)]
53     y_range = [polynomial.evaluate(x) for x in x_range]
54     f = plt.figure()

```

```

55     plt.plot(x_range, y_range)
56     plt.plot(data_x_points, data_y_points, 'oCO')
57     plt.xlabel('$H$')
58     plt.ylabel('$B$')
59     plt.grid(True)
60     f.savefig('report/plots/{}.pdf'.format(filename), bbox_inches='tight')
61
62
63 if __name__ == '__main__':
64     q1()

```

Listing 3: Custom polynomial class (*polynomial.py*).

```

1  class Polynomial:
2      def __init__(self, coefficients):
3          self.coefficients = coefficients
4          self.order = len(coefficients) - 1
5
6      def __getitem__(self, item):
7          return self.coefficients[item]
8
9      def __add__(self, other):
10         result_coefficients = []
11         common_order = min(self.order, other.order)
12         for i in range(common_order + 1):
13             result_coefficients.append(self[i] + other[i])
14         if self.order > other.order:
15             for i in range(common_order + 1, self.order + 1):
16                 result_coefficients.append(self[i])
17         elif other.order > self.order:
18             for i in range(common_order + 1, other.order + 1):
19                 result_coefficients.append(other[i])
20         return Polynomial(result_coefficients)
21
22     def __sub__(self, other):
23         result_coefficients = []
24         common_order = min(self.order, other.order)
25         for i in range(common_order + 1):
26             result_coefficients.append(self[i] - other[i])
27         if self.order > other.order:
28             for i in range(common_order + 1, self.order + 1):
29                 result_coefficients.append(self[i])
30         elif other.order > self.order:
31             for i in range(common_order + 1, other.order + 1):
32                 result_coefficients.append(-other[i])
33         return Polynomial(result_coefficients)
34
35     def __mul__(self, other):
36         result_coefficients = []
37         max_result_order = self.order + other.order
38         for result_order in range(max_result_order + 1):
39             coefficient = 0
40             for order1 in range(self.order + 1):
41                 for order2 in range(other.order + 1):
42                     if order1 + order2 == result_order:
43                         coefficient += self[order1] * other[order2]
44             result_coefficients.append(coefficient)
45         return Polynomial(result_coefficients)
46
47     def __str__(self):
48         return ' + '.join('{}x{}'.format(coefficient, power) for power, coefficient in
49             ↪ enumerate(self.coefficients))
50
51     def scalar_multiply(self, scalar):
52         return Polynomial([scalar * coefficient for coefficient in self.coefficients])
53
54     def evaluate(self, x):
55         result = 0
56         for power, coefficient in enumerate(self.coefficients):

```

```

56         result += coefficient * (x ** power)
57     return result

```

Listing 4: Tests of the custom polynomial class (test_polynomial.py).

```

1  import unittest
2
3  from polynomial import Polynomial
4
5
6  class TestPolynomial(unittest.TestCase):
7      def test__add__(self):
8          p1 = Polynomial([4, 5, 6])
9          p2 = Polynomial([4, 5, 6, 7, 8])
10         expected_coefficients = [8, 10, 12, 7, 8]
11
12         p3 = (p1 + p2)
13         actual_coefficients = p3.coefficients
14
15         self.assertEqual(expected_coefficients, actual_coefficients)
16         print('{} + {} = {}'.format(p1, p2, p3))
17
18     def test__sub__(self):
19         p1 = Polynomial([4, 5, 6])
20         p2 = Polynomial([4, 5, 6, 7, 8])
21         expected_coefficients = [0, 0, 0, -7, -8]
22
23         p3 = (p1 - p2)
24         actual_coefficients = p3.coefficients
25
26         self.assertEqual(expected_coefficients, actual_coefficients)
27         print('{} - {} = {}'.format(p1, p2, p3))
28
29     def test__mul__(self):
30         p1 = Polynomial([4, 5, 6])
31         p2 = Polynomial([4, 5, 6, 7, 8])
32         expected_coefficients = [16, 40, 73, 88, 103, 82, 48]
33
34         p3 = (p1 * p2)
35         actual_coefficients = p3.coefficients
36
37         self.assertEqual(expected_coefficients, actual_coefficients)
38         print('{} * {} = {}'.format(p1, p2, p3))
39
40     def test_evaluate_0(self):
41         p1 = Polynomial([4, 5, 6])
42         expected = 4
43
44         actual = p1.evaluate(0)
45
46         self.assertEqual(expected, actual)
47
48     def test_evaluate_1(self):
49         p1 = Polynomial([4, 5, 6])
50         expected = 4 + 5 + 6
51
52         actual = p1.evaluate(1)
53
54         self.assertEqual(expected, actual)
55
56     def test_evaluate_2(self):
57         p1 = Polynomial([4, 5, 6])
58         expected = 4 + 10 + 24
59
60         actual = p1.evaluate(2)
61
62         self.assertEqual(expected, actual)
63
64

```

```

65 if __name__ == '__main__':
66     unittest.main()

```

Listing 5: Lagrange interpolation (lagrange.py).

```

1  from __future__ import division
2
3  from polynomial import Polynomial
4
5
6  def lagrange_interpolation(x_values, y_values):
7      n = len(x_values)
8      result_polynomial = Polynomial([])
9      for j in range(n):
10         result_polynomial += lagrange_lj_polynomial(j, x_values).scalar_multiply(y_values[j])
11     return result_polynomial
12
13
14 def lagrange_lj_polynomial(j, x_values):
15     fj_x = lagrange_fj_polynomial(j, x_values)
16     fj_xj = lagrange_fj_constant_denominator(j, x_values)
17     return fj_x.scalar_multiply(1 / fj_xj)
18
19
20 def lagrange_fj_polynomial(j, x_values):
21     result_polynomial = Polynomial([1])
22     for r in range(len(x_values)):
23         if r != j:
24             result_polynomial *= Polynomial([-x_values[r], 1])
25     return result_polynomial
26
27
28 def lagrange_fj_constant_denominator(j, x_values):
29     product = 1
30     for r, x_r in enumerate(x_values):
31         if r != j:
32             product *= (x_values[j] - x_r)
33     return product

```

Listing 6: Tests of the Lagrange interpolation (test_lagrange.py).

```

1  import unittest
2
3  from lagrange import lagrange_fj_polynomial, lagrange_interpolation
4
5
6  class TestLagrange(unittest.TestCase):
7      def test_lagrange_fj_polynomial(self):
8          expected_coefficients = [-1, 1]
9
10         actual_coefficients = (lagrange_fj_polynomial(1, [1, 2])).coefficients
11
12         self.assertEqual(expected_coefficients, actual_coefficients)
13
14     def test_lagrange_interpolation(self):
15         x_values = [1, 2, 3, 4, 5]
16         y_values = [4, 5, 1, 6, 10]
17
18         polynomial = lagrange_interpolation(x_values, y_values)
19
20         for x, y in zip(x_values, y_values):
21             self.assertEqual(y, polynomial.evaluate(x))
22
23
24 if __name__ == '__main__':
25     unittest.main()

```


Listing 7: Question 2 (q2.py).

```

1  import math
2
3  from piecewise_linear import PiecewiseLinearInterpolator
4  from successive_substitution import successive_substitution_solve
5  from newton_raphson import newton_raphson_solve
6
7  import matplotlib.pyplot as plt
8  from matplotlib import rc
9
10 rc('font', **{'family': 'serif', 'serif': ['Computer Modern']})
11 rc('text', usetex=True)
12
13
14 B = [0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9]
15 H = [0.0, 14.7, 36.5, 71.7, 121.4, 197.4, 256.2, 348.7, 540.6, 1062.8, 2317.0, 4781.9, 8687.4, 13924.3,
    ↪ 22650.2]
16 L_a = 5e-3
17 A = 1e-4
18 mu_0 = 4e-7 * math.pi
19 L_c = 0.3
20 N = 1000
21 I = 8
22
23
24 def q2():
25     print('\n=== Question 2 ===')
26     q2a()
27     q2b()
28     q2c()
29
30
31 def q2a():
32     print('\n=== Question 2(a) ===')
33     print('Flux equation: ')
34     coeff_1 = L_a / (A * mu_0)
35     print(coeff_1)
36     coeff_2 = L_c
37     coeff_3 = N * I
38     eq = 'f(\psi) = \SI{:1.3e}{{}} \psi + {}H(\psi) - {} = 0'.format(coeff_1, coeff_2, coeff_3)
39     print(eq)
40     with open('report/latex/flux_equation.txt', 'w') as f:
41         f.write(eq)
42
43
44 def q2b():
45     print('\n=== Question 2(b) ===')
46     flux, iterations = newton_raphson_solve()
47     print('Solved flux: {:1.3e} Wb'.format(flux))
48     print('Number of iterations: {}'.format(iterations))
49     plot_interpolation(0.0, 1.9, PiecewiseLinearInterpolator(), B, H)
50
51
52 def q2c():
53     print('\n=== Question 2(c) ===')
54     flux, iterations = successive_substitution_solve()
55     print('Solved flux: {:1.3e} Wb'.format(flux))
56     print('Number of iterations: {}'.format(iterations))
57
58
59 def plot_interpolation(x_min, x_max, interpolator, data_x_points, data_y_points, num_points=1000,
    ↪ filename='q2b'):
60     subdivision = (x_max - x_min) / num_points
61     x_range = [x_min + i * subdivision for i in range(num_points)]
62     y_range = [interpolator.evaluate_b(x) for x in x_range]
63     f = plt.figure()
64     plt.plot(x_range, y_range)
65     plt.plot(data_x_points, data_y_points, 'oC0')

```

```

66     plt.xlabel('$B$')
67     plt.ylabel('$H$')
68     plt.grid(True)
69     f.savefig('report/plots/{}.pdf'.format(filename), bbox_inches='tight')
70
71
72 if __name__ == '__main__':
73     q2()

```

Listing 8: Newton-Raphson (newton_raphson.py).

```

1  from __future__ import division
2
3  import math
4
5  from piecewise_linear import PiecewiseLinearInterpolator
6  from slope_interpolation import SlopeInterpolation
7
8  L_a = 5e-3
9  A = 1e-4
10 mu_0 = 4e-7 * math.pi
11 EPSILON = 1e-6
12
13
14 def newton_raphson_solve():
15     h_interpolator = PiecewiseLinearInterpolator()
16     h_prime_interpolator = SlopeInterpolation()
17
18     flux = 0
19     f_0 = update_f(flux, h_interpolator)
20     f_prime = update_f_prime(flux, h_prime_interpolator)
21     f = f_0
22     iterations = 0
23     while abs(f / f_0) >= EPSILON:
24         print('Flux: {} Wb at iteration {}'.format(flux, iterations))
25         flux -= f / f_prime
26         f = update_f(flux, h_interpolator)
27         f_prime = update_f_prime(flux, h_prime_interpolator)
28         iterations += 1
29     return flux, iterations
30
31
32 def update_f(flux, h_interpolator):
33     return L_a / (A * mu_0) * flux + 0.3 * h_interpolator.evaluate_flux(flux) - 8000
34
35
36 def update_f_prime(flux, h_prime_interpolator):
37     return L_a / (A * mu_0) + 3000 * h_prime_interpolator.evaluate_flux(flux)

```

Listing 9: Piecewise-linear interpolation (piecewise_linear.py).

```

1  from __future__ import division
2
3  from lagrange import lagrange_interpolation
4
5  B = [0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9]
6  H = [0.0, 14.7, 36.5, 71.7, 121.4, 197.4, 256.2, 348.7, 540.6, 1062.8, 2317.0, 4781.9, 8687.4, 13924.3,
   ↪ 22650.2]
7  A = 1e-4
8
9
10 class PiecewiseLinearInterpolator:
11     def __init__(self):
12         self.piecewise_linear_polynomials = []
13         for i in range(len(B) - 1):
14             x_values = B[i:i + 2]
15             y_values = H[i:i + 2]
16             lagrange_interpolation_polynomial = lagrange_interpolation(x_values, y_values)

```

```

17         self.pieceswise_linear_polynomials.append(lagrange_interpolation_polynomial)
18
19     def evaluate_flux(self, flux):
20         b = flux / A
21         return self.evaluate_b(b)
22
23     def evaluate_b(self, b):
24         if b > B[-1]:
25             return self.pieceswise_linear_polynomials[-1].evaluate(b)
26         elif b < B[0]:
27             return self.pieceswise_linear_polynomials[0].evaluate(b)
28         for i in range(len(B) - 1):
29             if B[i] <= b <= B[i + 1]:
30                 return self.pieceswise_linear_polynomials[i].evaluate(b)
31         return None

```

Listing 10: Slope interpolation (slope_interpolation.py).

```

1  from __future__ import division
2
3  B = [0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9]
4  H = [0.0, 14.7, 36.5, 71.7, 121.4, 197.4, 256.2, 348.7, 540.6, 1062.8, 2317.0, 4781.9, 8687.4, 13924.3,
5      ↪ 22650.2]
6  A = 1e-4
7
8  class SlopeInterpolation:
9      def __init__(self):
10         self.slopes = []
11         for i in range(len(B) - 1):
12             h_slope = (H[i + 1] - H[i]) / (B[i + 1] - B[i])
13             self.slopes.append(h_slope)
14
15     def evaluate_flux(self, flux):
16         b = flux / A
17         return self.evaluate_b(b)
18
19     def evaluate_b(self, b):
20         if b > B[-1]:
21             return self.slopes[-1]
22         elif b < B[0]:
23             return self.slopes[0]
24         for i in range(len(B) - 1):
25             if B[i] <= b <= B[i + 1]:
26                 return self.slopes[i]
27         return None

```

Listing 11: Successive substitution (successive_substitution.py).

```

1  from __future__ import division
2
3  import math
4
5  from piecewise_linear import PiecewiseLinearInterpolator
6  from piecewise_linear_inverse import PiecewiseLinearInterpolatorInverse
7
8  L_a = 5e-3
9  A = 1e-4
10 mu_0 = 4e-7 * math.pi
11 EPSILON = 1e-6
12
13
14 def successive_substitution_solve():
15     h_interpolator = PiecewiseLinearInterpolator()
16     b_interpolator = PiecewiseLinearInterpolatorInverse()
17
18     flux = 1e-6
19     f_0 = update_f(flux, h_interpolator)

```

```

20     f = f_0
21     iterations = 0
22     while abs(f / f_0) >= EPSILON:
23         print('Flux: {} Wb at iteration {}'.format(flux, iterations))
24         flux = update_flux4(flux, b_interpolator)
25         f = update_f(flux, h_interpolator)
26         iterations += 1
27     return flux, iterations
28
29
30 def update_f(flux, h_interpolator):
31     return L_a / (A * mu_0) * flux + 0.3 * h_interpolator.evaluate_flux(flux) - 8000
32
33
34 def update_flux(flux, h_interpolator):
35     return (8000 - 0.3 * h_interpolator.evaluate_flux(flux)) / (L_a / (A * mu_0))
36
37
38 def update_flux2(flux, h_interpolator):
39     return 8000 / ((L_a / (A * mu_0)) + 0.3 * h_interpolator.evaluate_flux(flux) / flux)
40
41
42 def update_flux3(flux, h_interpolator):
43     return 0.3 * h_interpolator.evaluate_flux(flux) / (8000 / flux - (L_a / (A * mu_0)))
44
45
46 def update_flux4(flux, b_interpolator):
47     return A * b_interpolator.evaluate_h((8000 - (L_a / (A * mu_0)) * flux) / 0.3)

```

Listing 12: B-H piecewise-linear interpolation (piecewise_linear_inverse.py).

```

1  from __future__ import division
2
3  from lagrange import lagrange_interpolation
4
5  B = [0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9]
6  H = [0.0, 14.7, 36.5, 71.7, 121.4, 197.4, 256.2, 348.7, 540.6, 1062.8, 2317.0, 4781.9, 8687.4, 13924.3,
7      ↪ 22650.2]
8  A = 1e-4
9
10 class PiecewiseLinearInterpolatorInverse:
11     def __init__(self):
12         self.piecewise_linear_polynomials = []
13         for i in range(len(B) - 1):
14             x_values = H[i:i + 2]
15             y_values = B[i:i + 2]
16             lagrange_interpolation_polynomial = lagrange_interpolation(x_values, y_values)
17             self.piecewise_linear_polynomials.append(lagrange_interpolation_polynomial)
18
19     def evaluate_h(self, h):
20         if h > H[-1]:
21             return self.piecewise_linear_polynomials[-1].evaluate(h)
22         elif h < H[0]:
23             return self.piecewise_linear_polynomials[0].evaluate(h)
24         for i in range(len(B) - 1):
25             if H[i] <= h <= H[i + 1]:
26                 return self.piecewise_linear_polynomials[i].evaluate(h)
27         return None

```

Listing 13: Piecewise-linear interpolation tests (test_piecewise_linear.py).

```

1  import unittest
2
3  from piecewise_linear import PiecewiseLinearInterpolator
4
5  B = [0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9]

```

```

6 H = [0.0, 14.7, 36.5, 71.7, 121.4, 197.4, 256.2, 348.7, 540.6, 1062.8, 2317.0, 4781.9, 8687.4, 13924.3,
  ↪ 22650.2]
7 A = 1e-4
8
9
10 class TestPiecewiseLinearInterpolation(unittest.TestCase):
11     def test_evaluate(self):
12         interpolator = PiecewiseLinearInterpolator()
13         for b, h in zip(B, H):
14             self.assertAlmostEqual(h, interpolator.evaluate_b(b))
15             self.assertAlmostEqual(h, interpolator.evaluate_flux(b * A))
16
17
18 if __name__ == '__main__':
19     unittest.main()

```

Listing 14: Slope interpolation tests (test_slope_interpolation.py).

```

1 import unittest
2
3 from slope_interpolation import SlopeInterpolation
4
5 B = [0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9]
6 H = [0.0, 14.7, 36.5, 71.7, 121.4, 197.4, 256.2, 348.7, 540.6, 1062.8, 2317.0, 4781.9, 8687.4, 13924.3,
  ↪ 22650.2]
7 A = 1e-4
8
9
10 class TestPiecewiseLinearInterpolation(unittest.TestCase):
11     def test_evaluate(self):
12         interpolator = SlopeInterpolation()
13         for i in range(len(B) - 1):
14             h_slope = (H[i + 1] - H[i]) / (B[i + 1] - B[i])
15             self.assertAlmostEqual(h_slope, interpolator.evaluate_b(B[i] + 0.01))
16             self.assertAlmostEqual(h_slope, interpolator.evaluate_flux((B[i] + 0.01) * A))
17
18
19 if __name__ == '__main__':
20     unittest.main()

```

Listing 15: Question 3 (q3.py).

```

1 from __future__ import division
2
3 from data_saver import save_rows_to_latex
4 from newton_raphson_matrix import newton_raphson_matrix_solve
5
6
7 import numpy as np
8 import numpy.polynomial.polynomial as poly
9 import sympy as sp
10 import matplotlib.pyplot as plt
11 from matplotlib import rc
12
13 rc('font', **{'family': 'serif', 'serif': ['Computer Modern']})
14 rc('text', usetex=True)
15
16
17 def q3():
18     print('\n=== Question 3 ===')
19     v_n, error_values, norm_values, vA_values, vB_values, fA_values, fB_values =
  ↪ newton_raphson_matrix_solve()
20     print('Solution: {}'.format(v_n))
21     v_a, v_b = v_n.values
22     print('v_a: {:.3f} mV'.format(v_a * 1000))
23     print('v_b: {:.3f} mV'.format(v_b * 1000))
24     save_rows_to_latex('report/latex/q3.txt', zip(vA_values, vB_values, fA_values, fB_values))
25     plot_error(error_values)

```

```

26     plot_error_quadratic_fit(error_values)
27
28
29 def plot_error(error_values):
30     x_range = [i for i in range(len(error_values))]
31     y_range = error_values
32     f = plt.figure()
33     plt.plot(x_range, y_range, 'o-')
34     plt.xlabel('Step')
35     plt.ylabel('Error')
36     plt.grid(True)
37     f.savefig('report/plots/q3.pdf', bbox_inches='tight')
38
39
40 def plot_error_quadratic_fit(error_values):
41     f = plt.figure()
42
43     x_range = [i for i in range(len(error_values))]
44     y_range = [float(error) for error in error_values]
45     print(y_range)
46     plt.plot(x_range, y_range, 'o')
47
48     x_new = np.linspace(x_range[0], x_range[-3], num=len(x_range) * 10)
49     polynomial_coeffs = poly.polyfit(x_range, y_range, deg=2)
50     polynomial_fit = poly.polyval(x_new, polynomial_coeffs)
51     N = sp.symbols("1/h")
52     poly_label = sum(sp.S("{:.5f}".format(v)) * N ** i for i, v in enumerate(polynomial_coeffs))
53     equation = '${}$.format(sp.printing.latex(poly_label))
54     plt.plot(x_new, polynomial_fit, 'C0-', label=equation)
55
56     plt.xlabel('Step')
57     plt.ylabel('Error')
58     plt.grid(True)
59     plt.legend()
60     f.savefig('report/plots/q3_fit.pdf', bbox_inches='tight')
61
62
63 if __name__ == '__main__':
64     q3()

```

Listing 16: Newton-Raphson (newton_raphson_matrix.py).

```

1  from __future__ import division
2
3  import copy
4  from math import exp
5
6  from matrices import Matrix
7
8  E = 220e-3
9  R = 500
10 I_SA = 0.6e-6
11 I_SB = 1.2e-6
12 kT_q = 25e-3
13
14 EPSILON = 1e-9
15
16
17 def newton_raphson_matrix_solve():
18     error_values = []
19     norm_values = []
20     vA_values = []
21     vB_values = []
22     fA_values = []
23     fB_values = []
24
25     iteration = 1
26     v_n = Matrix.empty(2, 1)
27     f = Matrix.empty(2, 1)

```

```

28     F = Matrix.empty(2, 2)
29     update_f(f, v_n)
30     f_0 = copy.deepcopy(f)
31     update_jacobian(F, v_n)
32
33     error_values.append('{:.3e}'.format(f.two_norm / f_0.two_norm))
34     norm_values.append('{:.3e}'.format(f.two_norm))
35     vA_values.append(v_n.scaled_values(1000)[0])
36     vB_values.append(v_n.scaled_values(1000)[1])
37     fA_values.append('{:.3e}'.format(f.values[0]))
38     fB_values.append('{:.3e}'.format(f.values[1]))
39
40     while f.two_norm / f_0.two_norm >= EPSILON:
41         v_n -= inverse_2x2(F) * f
42         update_f(f, v_n)
43         update_jacobian(F, v_n)
44         iteration += 1
45
46         error_values.append('{:.3e}'.format(f.two_norm / f_0.two_norm))
47         norm_values.append('{:.3e}'.format(f.two_norm))
48         vA_values.append(v_n.scaled_values(1000)[0])
49         vB_values.append(v_n.scaled_values(1000)[1])
50         fA_values.append('{:.3e}'.format(f.values[0]))
51         fB_values.append('{:.3e}'.format(f.values[1]))
52     return v_n, error_values, norm_values, vA_values, vB_values, fA_values, fB_values
53
54
55 def update_f(f, v_n):
56     v_a, v_b = v_n.values
57     f[0][0] = f_a(v_a, v_b)
58     f[1][0] = f_b(v_a, v_b)
59
60
61 def update_jacobian(F, v_n):
62     v_a, v_b = v_n.values
63     F[0][0] = dfa_dva(v_a, v_b)
64     F[0][1] = dfa_dvb(v_a, v_b)
65     F[1][0] = dfb_dva(v_a, v_b)
66     F[1][1] = dfb_dvb(v_a, v_b)
67
68
69 def f_a(v_a, v_b):
70     return v_a + R * I_SA * exp_f_term(v_a, v_b) - E
71
72
73 def f_b(v_a, v_b):
74     return I_SA * exp_f_term(v_a, v_b) - I_SB * exp_f_term(0, -v_b)
75
76
77 def dfa_dva(v_a, v_b):
78     return 1 + R * I_SA * exp_df_term(v_a, v_b)
79
80
81 def dfa_dvb(v_a, v_b):
82     return -R * I_SA * exp_df_term(v_a, v_b)
83
84
85 def dfb_dva(v_a, v_b):
86     return I_SA * exp_df_term(v_a, v_b)
87
88
89 def dfb_dvb(v_a, v_b):
90     return -I_SA * exp_df_term(v_a, v_b) - I_SB * exp_df_term(0, -v_b)
91
92
93 def exp_f_term(v_a, v_b):
94     return exp((v_a - v_b) / kT_q) - 1
95
96
97 def exp_df_term(v_a, v_b):

```

```

98     return exp((v_a - v_b) / kT_q) / kT_q
99
100
101 def inverse_2x2(A):
102     a = A[0][0]
103     b = A[0][1]
104     c = A[1][0]
105     d = A[1][1]
106     inverse = Matrix([
107         [d, -b],
108         [-c, a]
109     ])
110     return inverse.scalar_divide(a * d - b * c)

```

Listing 17: Question 4 (q4.py).

```

1  from __future__ import division
2
3  from math import cos, log10, sin, log
4  from matplotlib.patches import Rectangle
5  from gauss_legendre import one_point_gauss_legendre, one_point_gauss_legendre_arbitrary_widths, \
6      convert_relative_widths_to_widths
7
8  import matplotlib.pyplot as plt
9  from matplotlib import rc
10 rc('font', **{'family': 'serif', 'serif': ['Computer Modern']})
11 rc('text', usetex=True)
12
13
14 def q4():
15     print('\n=== Question 4 ===')
16     q4a()
17     q4b()
18     q4c()
19
20
21 def q4a():
22     print('\n=== Question 4(a) ===')
23     n_values = []
24     integrals = []
25     n_max = 20
26     actual_integral = sin(1)
27     print('Actual integral of cos(x): {}'.format(actual_integral))
28     for n in range(1, n_max + 1):
29         integral = one_point_gauss_legendre(n, func=cos)
30         n_values.append(n)
31         integrals.append(integral)
32         print('Integral of cos(x) with N={}: {}'.format(n, integral))
33         print('Error: {}'.format(abs(actual_integral - integral)))
34     plot_error(n_values, integrals, actual_integral, func=cos, filename='q4a')
35
36
37 def q4b():
38     print('\n=== Question 4(b) ===')
39     n_values = []
40     integrals = []
41     n_max = 200
42     actual_integral = -1
43     print('Actual integral of ln(x): {}'.format(actual_integral))
44     for n in range(10, n_max + 1, 10):
45         integral = one_point_gauss_legendre(n, func=log)
46         n_values.append(n)
47         integrals.append(integral)
48         print('Integral of ln(x) with N={}: {}'.format(n, integral))
49         print('Error: {}'.format(abs(actual_integral - integral)))
50     plot_error(n_values, integrals, actual_integral, func=log, filename='q4b')
51
52
53 def q4c():

```



```

54     print('\n=== Question 4(c) ===')
55     actual_integral = -1
56     print('Actual integral of ln(x): {}'.format(actual_integral))
57     relative_widths = [x for x in range(1, 11)]
58     print('Relative widths: {}'.format(relative_widths))
59     widths = convert_relative_widths_to_widths(relative_widths)
60     print('Actual widths: {}'.format(widths))
61     integral = one_point_gauss_legendre_arbitrary_widths(widths, func=log)
62     print('Estimated Integral of ln(x): {}'.format(integral))
63     print('Error: {}'.format(abs(actual_integral - integral)))
64     plot_log_widths(widths)
65
66
67 def plot_error(n_values, integrals, actual_integral, func, filename='q4a'):
68     x_range = [log10(n) for n in n_values]
69     y_range = [log10(abs(actual_integral - integral)) for integral in integrals]
70     f = plt.figure()
71     plt.plot(x_range, y_range, 'o-')
72     plt.xlabel('$\log_{10}\{N\}$')
73     plt.ylabel('$\log_{10}\{E\}$')
74     plt.grid(True)
75     f.savefig('report/plots/{}.pdf'.format(filename), bbox_inches='tight')
76
77
78 def plot_log_widths(widths):
79     x_range = [i / 100 for i in range(1, 101)]
80     y_range = [log(x) for x in x_range]
81     f = plt.figure()
82     plt.plot(x_range, y_range, 'C9')
83     axis = plt.gca()
84     width_sum = 0
85     for w in widths:
86         axis.add_patch(Rectangle((width_sum, 0), w, log(width_sum + w / 2), facecolor='C0'))
87         width_sum += w
88
89     plt.xlabel('$x$')
90     plt.ylabel('$\log_e x$')
91     plt.grid(True)
92     f.savefig('report/plots/q4c.pdf', bbox_inches='tight')
93
94
95 if __name__ == '__main__':
96     q4()

```

Listing 18: Gauss-Legendre integration (*gauss_legendre.py*).

```

1  from __future__ import division
2
3
4  def one_point_gauss_legendre(n, func):
5      integral = 0
6      for i in range(n):
7          integral += func((i + 0.5) / n)
8      return integral / n
9
10
11 def one_point_gauss_legendre_arbitrary_widths(widths, func):
12     integral = 0
13     width_sum = 0
14     for h in widths:
15         integral += h * func(width_sum + h / 2)
16         width_sum += h
17     return integral
18
19
20 def convert_relative_widths_to_widths(relative_widths):
21     sum_relative_widths = sum(relative_widths)
22     return [r / sum_relative_widths for r in relative_widths]

```

B Output Logs

Listing 19: Output of Question 1 program (q1.txt).

```
1  === Question 1 ===
2
3  === Question 1(a) ===
4  B: [0.0, 0.2, 0.4, 0.6, 0.8, 1.0]
5  H: [0.0, 14.7, 36.5, 71.7, 121.4, 197.4]
6  Interpolation polynomial: 0.0x^0 + 0.0160250789192x^1 + -0.000184937790227x^2 + 1.46891994659e-06x^3 +
   ↪ -5.95091845404e-09x^4 + 9.27493520842e-12x^5
7
8  === Question 1(b) ===
9  B: [0.0, 1.3, 1.4, 1.7, 1.8, 1.9]
10 H: [0.0, 540.6, 1062.8, 8687.4, 13924.3, 22650.2]
11 Interpolation polynomial: 0.0x^0 + 0.00380360001675x^1 + -2.8640158825e-06x^2 + 5.30016232425e-10x^3 +
   ↪ -3.50510926118e-14x^4 + 7.46724167973e-19x^5
```

Listing 20: Output of Question 2 program (q2.txt).

```
1  === Question 2 ===
2
3  === Question 2(a) ===
4  Flux equation:
5  39788735.773
6  f(\psi) = \SI{3.979e+07}{\psi} \psi + 0.3H(\psi) - 8000 = 0
7
8  === Question 2(b) ===
9  Flux: 0 Wb at iteration 0
10 Flux: 0.000199953831795 Wb at iteration 1
11 Flux: 0.000168926916944 Wb at iteration 2
12 Solved flux: 1.613e-04 Wb
13 Number of iterations: 3
14
15 === Question 2(c) ===
16 Flux: 1e-06 Wb at iteration 0
17 Flux: 0.000194450930617 Wb at iteration 1
18 Flux: 0.000136438357006 Wb at iteration 2
19 Flux: 0.000169701875678 Wb at iteration 3
20 Flux: 0.000157473959843 Wb at iteration 4
21 Flux: 0.000162558274405 Wb at iteration 5
22 Flux: 0.0001608316628 Wb at iteration 6
23 Flux: 0.000161418012759 Wb at iteration 7
24 Flux: 0.000161218890806 Wb at iteration 8
25 Flux: 0.000161286511775 Wb at iteration 9
26 Flux: 0.000161263547981 Wb at iteration 10
27 Flux: 0.000161271346388 Wb at iteration 11
28 Flux: 0.000161268698082 Wb at iteration 12
29 Flux: 0.000161269597436 Wb at iteration 13
30 Flux: 0.000161269292019 Wb at iteration 14
31 Solved flux: 1.613e-04 Wb
32 Number of iterations: 15
```

Listing 21: Output of Question 3 program (q3.txt).

```
1  === Question 3 ===
2  Solution:
3  0.198
4  0.091
5  v_a: 198.134 mV
6  v_b: 90.571 mV
```

Listing 22: Output of Question 4 program (q4.txt).

```
1  === Question 4 ===
2
```

```

3  === Question 4(a) ===
4  Actual integral of cos(x): 0.841470984808
5  Integral of cos(x) with N=1: 0.87758256189
6  Error: 0.0361115770825
7  Integral of cos(x) with N=2: 0.850300645292
8  Error: 0.00882966048434
9  Integral of cos(x) with N=3: 0.845379345845
10 Error: 0.00390836103756
11 Integral of cos(x) with N=4: 0.843666316703
12 Error: 0.00219533189465
13 Integral of cos(x) with N=5: 0.84287507437
14 Error: 0.00140408956194
15 Integral of cos(x) with N=6: 0.842445699196
16 Error: 0.00097471438853
17 Integral of cos(x) with N=7: 0.842186947503
18 Error: 0.000715962695571
19 Integral of cos(x) with N=8: 0.842019067246
20 Error: 0.000548082438602
21 Integral of cos(x) with N=9: 0.841903996167
22 Error: 0.000433011359186
23 Integral of cos(x) with N=10: 0.841821700007
24 Error: 0.000350715199399
25 Integral of cos(x) with N=11: 0.841760817405
26 Error: 0.000289832597425
27 Integral of cos(x) with N=12: 0.841714515321
28 Error: 0.000243530512976
29 Integral of cos(x) with N=13: 0.841678483879
30 Error: 0.000207499070943
31 Integral of cos(x) with N=14: 0.841649895569
32 Error: 0.000178910761171
33 Integral of cos(x) with N=15: 0.84162683297
34 Error: 0.000155848162437
35 Integral of cos(x) with N=16: 0.841607958582
36 Error: 0.000136973773665
37 Integral of cos(x) with N=17: 0.841592316399
38 Error: 0.000121331591133
39 Integral of cos(x) with N=18: 0.841579208411
40 Error: 0.000108223603482
41 Integral of cos(x) with N=19: 0.841568115345
42 Error: 9.71305373565e-05
43 Integral of cos(x) with N=20: 0.841558644427
44 Error: 8.76596193864e-05
45
46 === Question 4(b) ===
47 Actual integral of ln(x): -1
48 Integral of ln(x) with N=10: -0.965759065346
49 Error: 0.0342409346539
50 Integral of ln(x) with N=20: -0.982775471974
51 Error: 0.0172245280263
52 Integral of ln(x) with N=30: -0.988493840287
53 Error: 0.0115061597127
54 Integral of ln(x) with N=40: -0.99136170096
55 Error: 0.00863829903958
56 Integral of ln(x) with N=50: -0.993085194472
57 Error: 0.00691480552777
58 Integral of ln(x) with N=60: -0.994235347382
59 Error: 0.00576465261812
60 Integral of ln(x) with N=70: -0.99505745201
61 Error: 0.00494254798958
62 Integral of ln(x) with N=80: -0.995674340479
63 Error: 0.00432565952117
64 Integral of ln(x) with N=90: -0.996154326326
65 Error: 0.0038456736739
66 Integral of ln(x) with N=100: -0.99653843074
67 Error: 0.00346156926044
68 Integral of ln(x) with N=110: -0.996852774507
69 Error: 0.00314722549297
70 Integral of ln(x) with N=120: -0.997114780254
71 Error: 0.00288521974554
72 Integral of ln(x) with N=130: -0.99733651478

```

```

73 Error: 0.00266348521974
74 Integral of ln(x) with N=140: -0.997526600199
75 Error: 0.00247339980084
76 Integral of ln(x) with N=150: -0.997691361245
77 Error: 0.00230863875481
78 Integral of ln(x) with N=160: -0.997835542661
79 Error: 0.00216445733879
80 Integral of ln(x) with N=170: -0.997962773572
81 Error: 0.00203722642786
82 Integral of ln(x) with N=180: -0.998075877171
83 Error: 0.00192412282897
84 Integral of ln(x) with N=190: -0.998177082672
85 Error: 0.00182291732836
86 Integral of ln(x) with N=200: -0.998268173714
87 Error: 0.00173182628625
88
89 === Question 4(c) ===
90 Actual integral of ln(x): -1
91 Relative widths: [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]
92 Actual widths: [0.01818181818181818, 0.03636363636363636, 0.05454545454545454, 0.07272727272727272,
  ↪ 0.09090909090909091, 0.10909090909090909, 0.12727272727272726, 0.14545454545454545,
  ↪ 0.16363636363636364, 0.18181818181818182]
93 Estimated Integral of ln(x): -0.988377436631
94 Error: 0.0116225633689

```