MA633L-Numerical Analysis

Lecture 42 : Numerical Differentiation - Shooting Methods

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Shooting Method

Shooting method

Consider the second-order BVP

$$y'' = f(x, y, y'), \quad a \leq x \leq b, y(a) = \alpha, y(b) = \beta$$

Steps in Shooting Method

1. Transform the BVP into IVP
2. Obtain the Solution of the IVP using Taylor Series/Euler’s/RK2/RK3/RK4...
3. Obtain the solution of the given BVP

Linear BVP: Shooting method

Now, let us consider two IVPs:

$$y'' = p(x)y' + q(x)y + r(x), \quad a \leq x \leq b, \quad y(a) = \alpha, y'(a) = 0 \tag{1}$$

and

$$y'' = p(x)y' + q(x)y, \quad a \leq x \leq b, \quad y(a) = 0, y'(a) = 1 \tag{2}$$

Linear BVP: Shooting method

Then both IVP (1) and (2) have a unique solution. Let $y_1(x)$ denote the solution to IVP (1) and let $y_2(x)$ denote the solution to IVP (2). That is,

$$y_1'' = p(x)y_1' + q(x)y_1 + r(x), \quad a \le x \le b, \quad y_1(a) = \alpha, y_1'(a) = 0 \tag{3}$$

and

$$y_2'' = p(x)y_2' + q(x)y_2, \quad a \le x \le b, \quad y_2(a) = 0, y_2'(a) = 1 \tag{4}$$

Assume that $y_2(b) \neq 0$. Define

$$y(x) = y_1(x) + \frac{\beta - y_1(b)}{y_2(b)} y_2(x) \tag{5}$$

Linear BVP: Shooting method

Then $y(x)$ is the solution of the BVP

$$y'' = p(x)y' + q(x)y + r(x), \quad a \leq x \leq b, \quad y(a) = \alpha, y(b) = \beta$$

For,

$$y'(x) = y_1'(x) + \frac{\beta - y_1(b)}{y_2(b)} y_2'(x)$$

$$y''(x) = y_1''(x) + \frac{\beta - y_1(b)}{y_2(b)} y_2''(x)$$

$$\begin{aligned}
\implies \; y'' &= p(x)y_1' + q(x)y_1 + r(x) + \frac{\beta - y_1(b)}{y_2(b)}(p(x)y_2' + q(x)y_2) \\
&= p(x)\left(y_1' + \frac{\beta - y_1(b)}{y_2(b)}y_2'\right) + q(x)\left(y_1 + \frac{\beta - y_1(b)}{y_2(b)}y_2\right) \\
&\quad + r(x) \\
&= p(x)y' + q(x)y + r(x)
\end{aligned}$$

Linear BVP: Shooting method

Further,

$$y(a) = y_1(a) + \frac{\beta - y_1(b)}{y_2(b)} y_2(a) = \alpha$$

and

$$y(b) = y_1(b) + \frac{\beta - y_1(b)}{y_2(b)} y_2(b) = \beta$$

Linear BVP: Shooting method

The shooting method for linear BVP is obtained by replacing it with two IVPs (1) and (2). First let us rewrite (1)

$$y'' = p(x)y' + q(x)y + r(x), \quad a \leq x \leq b, \quad y(a) = \alpha, y'(a) = 0 \tag{6}$$

as a system of two linear differential equations by taking $z_1(x) = y(x)$ and $z_2(x) = y'(x)$ so that

$$\begin{aligned} z_1'(x) &= z_2(x) \\ z_2'(x) &= p(x)z_2(x) + q(x)z_1(x) + r(x) \end{aligned}$$

for $a \leq x \leq b$ with $z_1(a) = \alpha, z_2(a) = 0.$

Linear BVP: Shooting method

Similarly we write (2)

$$y'' = p(x)y' + q(x)y, \quad a \leq x \leq b, \quad y(a) = 0, y'(a) = 1 \tag{7}$$

as system of two linear differential equations by taking $z_3(x) = y(x)$ and $z_4(x) = y'(x)$ so that

$$\begin{aligned} z_3'(x) &= z_4(x) \\ z_4'(x) &= p(x)z_4(x) + q(x)z_3(x) \end{aligned}$$

for $a \leq x \leq b$ with $z_3(a) = 0, z_4(a) = 1.$

Linear BVP: Shooting method

Solve this system of ODEs.

$$\begin{bmatrix} z_1' \\ z_2' \\ z_3' \\ z_4' \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ q(x) & p(x) & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & q(x) & p(x) \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} + \begin{bmatrix} 0 \\ r(x) \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} z_1(a) \\ z_2(a) \\ z_3(a) \\ z_4(a) \end{bmatrix} = \begin{bmatrix} \alpha \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Linear BVP: Shooting method

The final approximations are

$$y_{1,i} = z_1(x_i) + \frac{\beta - z_1(x_n)}{z_3(x_n)} z_3(x_i) \approx y_1(x_i)$$

and

$$y_{2,i} = z_1(x_i) + \frac{\beta - z_1(x_n)}{z_3(x_n)} z_4(x_i) \approx y_1'(x_i)$$

Linear BVP: Shooting method

Solve the following linear BVP using the linear shooting method

$$y'' = -3y' + 2y + 2x + 3, \quad 0 \leq x \leq 1 \quad y(0) = 2, y(1) = 1, h = 0.1$$

Linear BVP: Shooting method

The two IVPs are

$$y_1'' = -3y_1' + 2y_1 + 2x + 3, \quad 0 \le x \le 1 \quad y_1(0) = 2, y_1'(0) = 0$$

and

$$y_2'' = -3y_2' + 2y_2, \quad 0 \le x \le 1 \quad y_2(0) = 0, y_2'(0) = 1$$

$y(x)$ is defined by

$$y(x) = y_1(x) + \frac{1 - y_1(1)}{y_2(1)} y_2(x) \tag{8}$$

Linear BVP: Shooting method

The first four order IVPs are

$$z_1' = z_2, \quad 0 \le x \le 1 \quad z_1(0) = 2$$

$$z_2' = -3z_2 + 2z_1 + 2x + 3, \quad 0 \le x \le 1 \quad z_2(0) = 0$$

$$z_3' = z_4, \quad 0 \le x \le 1 \quad z_3(0) = 0$$

$$z_4' = -3z_4 + 2z_3, \quad 0 \le x \le 1 \quad z_4(0) = 1$$

Solve this system of ODEs.

Linear BVP: Shooting method

Solve this system of ODEs.

$$\begin{bmatrix} z_1' \\ z_2' \\ z_3' \\ z_4' \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 2 & -3 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 2 & -3 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 2x+3 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} z_1(0) \\ z_2(0) \\ z_3(0) \\ z_4(0) \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Linear BVP: Shooting method

Solve this system of ODEs.

$$\begin{bmatrix} z_1(x_i)' \\ z_2(x_i)' \\ z_3(x_i)' \\ z_4(x_i)' \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 2 & -3 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 2 & -3 \end{bmatrix} \begin{bmatrix} z_1(x_i) \\ z_2(x_i) \\ z_3(x_i) \\ z_4(x_i) \end{bmatrix} + \begin{bmatrix} 0 \\ 2(x_i) + 3 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} z_1(0) \\ z_2(0) \\ z_3(0) \\ z_4(0) \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$x_0 = 0, x_1 = 0.1, x_2 = 0.2, x_3 = 0.4, x_4 = 0.5$
$x_5 = 0.6, x_6 = 0.7, x_7 = 0.8, x_8 = 0.9, x_9 = 1.0$

Linear BVP: Shooting method

Using Euler's method, we get

$$z_1'(x_i) = \frac{z_1(x_{i+1}) - z_1(x_i)}{h}$$

and similarly for z_2, z_3 and z_4, we obtain

$$\begin{bmatrix} \frac{z_1(x_{i+1})-z_1(x_i)}{h} \\ \frac{z_2(x_{i+1})-z_2(x_i)}{h} \\ \frac{z_3(x_{i+1})-z_3(x_i)}{h} \\ \frac{z_4(x_{i+1})-z_4(x_i)}{h} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 2 & -3 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 2 & -3 \end{bmatrix} \begin{bmatrix} z_1(x_i) \\ z_2(x_i) \\ z_3(x_i) \\ z_4(x_i) \end{bmatrix} + \begin{bmatrix} 0 \\ 2(x_i) + 3 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} z_1(0) \\ z_2(0) \\ z_3(0) \\ z_4(0) \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Linear BVP: Shooting method

$$\begin{bmatrix} z_1(x_{i+1}) \\ z_2(x_{i+1}) \\ z_3(x_{i+1}) \\ z_4(x_{i+1}) \end{bmatrix} = \begin{bmatrix} z_1(x_i) \\ z_2(x_i) \\ z_3(x_i) \\ z_4(x_i) \end{bmatrix} + h \begin{bmatrix} 0 & 1 & 0 & 0 \\ 2 & -3 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 2 & -3 \end{bmatrix} \begin{bmatrix} z_1(x_i) \\ z_2(x_i) \\ z_3(x_i) \\ z_4(x_i) \end{bmatrix} + h \begin{bmatrix} 0 \\ 2(x_i) + 3 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} z_1(0) \\ z_2(0) \\ z_3(0) \\ z_4(0) \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Linear BVP: Shooting method

$$\begin{bmatrix} z_1(0.1) \\ z_2(0.1) \\ z_3(0.1) \\ z_4(0.1) \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ 0 \\ 1 \end{bmatrix} + 0.1 \begin{bmatrix} 0 & 1 & 0 & 0 \\ 2 & -3 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 2 & -3 \end{bmatrix} \begin{bmatrix} 2 \\ 0 \\ 0 \\ 1 \end{bmatrix} + 0.1 \begin{bmatrix} 0 \\ 3 \\ 0 \\ 0 \end{bmatrix}$$

$$\implies \begin{bmatrix} z_1(0.1) \\ z_2(0.1) \\ z_3(0.1) \\ z_4(0.1) \end{bmatrix} = \begin{bmatrix} 2 \\ 3.4 \\ 0.1 \\ 0.7 \end{bmatrix}$$

Linear BVP: Shooting method

$$\begin{bmatrix} z_1(0.2) \\ z_2(0.2) \\ z_3(0.2) \\ z_4(0.2) \end{bmatrix} = \begin{bmatrix} z_1(0.1) \\ z_2(0.1) \\ z_3(0.1) \\ z_4(0.1) \end{bmatrix} + 0.1 \begin{bmatrix} 0 & 1 & 0 & 0 \\ 2 & -3 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 2 & -3 \end{bmatrix} \begin{bmatrix} z_1(0.1) \\ z_2(0.1) \\ z_3(0.1) \\ z_4(0.1) \end{bmatrix} + 0.1 \begin{bmatrix} 0 \\ 2(0.1)+3 \\ 0 \\ 0 \end{bmatrix}$$

$$\implies \begin{bmatrix} z_1(0.2) \\ z_2(0.2) \\ z_3(0.2) \\ z_4(0.2) \end{bmatrix} = \begin{bmatrix} 2.34 \\ 5.98 \\ 0.17 \\ 0.51 \end{bmatrix}$$

Linear BVP: Shooting method

x_i	$z_1(x_i)$	$z_2(x_i)$	$z_3(x_i)$	$z_4(x_i)$
0	2.0000	0	0	1.0000
0.1	2.0000	3.4000	0.1000	0.7000
0.2	2.3400	5.9800	0.1700	0.5100
0.3	2.9380	8.0540	0.2210	0.3910
0.4	3.7434	9.8254	0.2601	0.3179
0.5	4.7259	11.4265	0.2919	0.2745
0.6	5.8686	12.9437	0.3193	0.2506
0.7	7.1630	14.4343	0.3444	0.2393
0.8	8.6064	15.9366	0.3683	0.2364
0.9	10.2000	17.4769	0.3920	0.2391
1.0	11.9477	19.0738	0.4159	0.2458

Linear BVP: Shooting method

The final approximations are

$$y_{1,i} = z_1(x_i) + \frac{\beta - z_1(x_n)}{z_3(x_n)} z_3(x_i) \approx y_1(x_i)$$

and

$$y_{2,i} = z_1(x_i) + \frac{\beta - z_1(x_n)}{z_3(x_n)} z_4(x_i) \approx y_1'(x_i)$$

$$y(x) = y_1(x) + \frac{1 - y_1(1)}{y_2(1)} y_2(x) \tag{9}$$

Linear BVP: Shooting method

The following table shows the approximations

x_i	$y_1(x_i)$	$y_2(x_i)$	$y(x_i)$	$yexact(x_i)$
0	2.0000	-6.9321	2.0000	2.0000
0.1000	1.3068	-4.1525	1.3068	1.4084
0.2000	0.8915	-2.3254	0.8915	1.0222
0.3000	0.6590	-1.1095	0.6590	0.7832
0.4000	0.5481	-0.2848	0.5481	0.6509
0.5000	0.5196	0.2902	0.5196	0.5971
0.6000	0.5486	0.7071	0.5486	0.6023
0.7000	0.6193	1.0247	0.6193	0.6529
0.8000	0.7218	1.2811	0.7218	0.7398
0.9000	0.8499	1.5011	0.8499	0.8569
1.0000	1.0000	1.7008	1.0000	1.0000

Linear BVP: Shooting method

Solve the following linear BVP using the linear shooting method

$$y'' = \frac{-2}{x}y' + \frac{2}{x^2}y + \frac{\sin(\ln(x))}{x^2}, \quad 0 \leq x \leq 2 \quad y(1) = 1, y(2) = 2$$

Linear BVP: Shooting method

The general solution of the DE is

$$y_{exact}(x) = c_1 x + c_2 \frac{1}{x^2} - \frac{3}{10}\sin(\ln x) - \frac{1}{10}\cosh(\ln x)$$

Upon using BVP, $c_2 = -0.0392070, c_1 = 1.1392$
The two IVPs are

$$y_1'' = \frac{-2}{x}y_1' + \frac{2}{x^2}y_1 + \frac{\sin(\ln(x))}{x^2}, \quad 0 \le x \le 2 \quad y_1(1) = 1, y_1'(1) = 0$$

and

$$y_2'' = \frac{-2}{x}y_2' + \frac{2}{x^2}y_2, \quad 0 \le x \le 2 \quad y_2(1) = 0, y_2'(1) = 1$$

$y(x)$ is defined by

$$y(x) = y_1(x) + \frac{2 - y_1(2)}{y_2(2)}y_2(x) \tag{10}$$

Linear BVP: Shooting method

The following table shows the approximations

x_i	$y_1(x_i)$	$y_2(x_i)$	$y(x_i)$	$y_{exact}(x_i)$	$\lvert y(x_i) - w_i \rvert$
1	1.0000	0.0000	1.0000	1.0000	
1.1000	1.0089	0.0912	1.0926	1.0926	1.43×10^{-7}
1.2000	1.0324	0.1685	1.1870	1.1870	1.34×10^{-7}
1.3000	1.0667	0.2360	1.2833	1.2833	9.78×10^{-8}
1.4000	1.1092	0.2965	1.3814	1.3814	6.02×10^{-8}
1.5000	1.1583	0.3518	1.4811	1.4811	3.06×10^{-8}
1.6000	1.2124	0.4031	1.5823	1.5823	1.08×10^{-8}
1.7000	1.2708	0.4513	1.6850	1.6850	5.43×10^{-10}
1.8000	1.3327	0.4971	1.7888	1.7888	5.05×10^{-9}
1.9000	1.3975	0.5409	1.8939	1.8939	4.41×10^{-9}
2.0000	1.4647	0.5833	2.0000	2.0000	

Nonlinear BVP: Shooting Method

Nonlinear BVP: Shooting method

The shooting technique of the nonlinear second-order boundary value problem

$$y'' = f(x, y, y'), a \le x \le b, y(a) = \alpha, y(b) = \beta$$

It is similar to the linear technique. However, the solution to a nonlinear problem can't be expressed as a linear combination of the solutions of two IVPs.
We approximate it using a sequence of IVPs involving a parameter t.

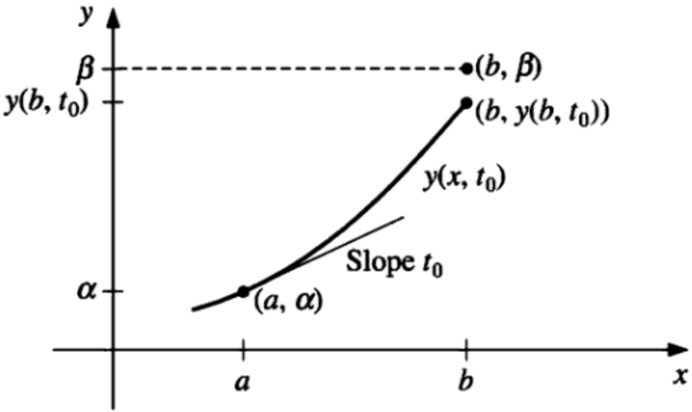
$$y'' = f(x, y, y'), a \le x \le b, y(a) = \alpha, y'(a) = t \tag{11}$$

Choose $t = t_k$ such that

$$\lim_{k \to \infty} y(b, t_k) = y(b) = \beta$$

Here, $y(x, t_k)$ denotes the solution of the IVP (11)

Nonlinear BVP: Shooting method



Nonlinear BVP: Shooting method

This technique is called a shooting method, as the procedure of firing objects at a stationary target.

- Start with a parameter t_0 that solves the IVP at which the object is fired from (a, α) and along the curve described by the solution to the IVP

$$y'' = f(x, y, y'), a \leq x \leq b, y(a) = \alpha, y'(a) = t_0$$

- If $y(b, t_0)$ is sufficiently close to β stop
- If $y(b, t_0)$ is not sufficiently close to β, correct our approximations by choosing $t_1, t_2 \cdots$ until $y(b, t_k)$ is sufficiently close to hitting β.

Nonlinear BVP: Shooting method

To find t_k, the BVP must satisfy the conditions of the theorem,m, which we discussed earlier (unique solution). To find t, it should satisfy $y(b,t) - \beta = 0$, which is a nonlinear equation. We can use the Newton-Raphson method or the Secant method to find t. In the secant method, with initial approximations t_0, t_1, we have

$$t_k = t_{k-1} - \frac{t_{k-1} - t_{k-2}}{y(b, t_{k-1}) - y(b, t_{k-2})}(y(b, t_{k-1}) - \beta)$$

Nonlinear BVP: Shooting method

Solve the following nonlinear BVP using the nonlinear shooting method

$$y'' = y^3 - yy', \quad 1 \leq x \leq 2 \quad y(1) = 1/2, y(2) = 1/3, h = 0.1$$

Nonlinear BVP: Shooting method

The IVP is

$$y'' = y^3 - yy', \quad 1 \le x \le 2 \quad y(1) = 1/2, y'(1) = t_0$$

Let $z_1(x) = y(x), z_2 = y'(x)$ and $t_0 = \frac{1/3-1/2}{2-1} = -1/6$ The first two order IVPs are

$$z_1' = z_2, \; 1 \le x \le 2, z_1(1) = 1/2$$

$$z_2' = z_1^3 - z_1 z_2, \; 1 \le x \le 2, z_2(1) = -1/6$$

Nonlinear BVP: Shooting method

Now use Euler's method or the RK4 method to solve the problem. Here, the explicit Euler method is used.

$$\frac{1}{h}(z_1(x_{i+1}) - z_1(x_i)) = z_2(x_i)$$

$$z_1(x_{i+1}) = hz_2(x_i) + z_1(x_i)$$

$$z_1(1.1) = 0.1z_2(1) + z_1(1) = 0.1 * (-1/6) + 1/2 = 0.4833$$

$$z_2(x_{i+1}) = h * (z_1(x_i)^3 - z_1(x_i)z_2(x_i)) + z_2(x_i)$$

$$z_2(1.1) = 0.1(z_1(1)^3 - z_1(1)z_2(1)) + z_2(1)$$

$$z_2(1.1) = 0.1((1/2)^3 - (1/2)(-1/6)) + (-1/6) = -0.1458$$

$$z_1(1.2) = 0.1z_2(1.1) + z_1(1.1) = 0.1 * (-0.1458) + 0.4833 = 0.4687$$

$$z_2(1.1) = 0.1((1/2)^3 - (1/2)(-1/6)) + (-1/6) = -0.1458$$

Nonlinear BVP: Shooting method

x_i	z_1	z_2
0	0.5000	-0.1667
0.1000	0.4833	-0.1458
0.2000	0.4688	-0.1275
0.3000	0.4560	-0.1112
0.4000	0.4449	-0.0967
0.5000	0.4352	-0.0836
0.6000	0.4269	-0.0717
0.7000	0.4197	-0.0608
0.8000	0.4136	-0.0509
0.9000	0.4085	-0.0417
1.0000	0.4043	-0.0332

Nonlinear BVP: Shooting method

Let $z_1(x) = y(x), z_2 = y'(x)$ and $t_1 = -1/8$ The first two order IVPs are

$$z_1' = z_2, \;\; 1 \leq x \leq 2, z_1(1) = 1/2$$

$$z_2' = z_1^3 - z_1 z_2, \;\; 1 \leq x \leq 2, z_2(1) = -1/8$$

and solve in the same way

Nonlinear BVP: Shooting method

x_i	z_1	z_2
0	0.5000	-0.1250
0.1000	0.4875	-0.1062
0.2000	0.4769	-0.0895
0.3000	0.4679	-0.0744
0.4000	0.4605	-0.0606
0.5000	0.4544	-0.0481
0.6000	0.4496	-0.0365
0.7000	0.4460	-0.0258
0.8000	0.4434	-0.0158
0.9000	0.4418	-0.0064
1.0000	0.4412	0.0026

Nonlinear BVP: Shooting method

$$t_0 = -1/6, t_1 = -1/8$$

$$y(b, t_0) = 0.4043, y(b, t_1) = 0.4412$$

$$t_k = t_{k-1} - \frac{t_{k-1} - t_{k-2}}{y(b, t_{k-1}) - y(b, t_{k-2})}(y(b, t_{k-1}) - \beta)$$

$$t_2 = t_1 - \frac{t_1 - t_0}{y(b, t_1) - y(b, t_0)}(y(b, t_1) - 1/3)$$

$$t_2 = -1/8 - \frac{-1/8 - (-1/6)}{0.4412 - 0.4043}(0.4043 - 1/3) = -0.2051$$

Nonlinear BVP: Shooting method

Let $z_1(x) = y(x), z_2 = y'(x)$ and $t_2 = -0.2051$ The first two order IVPs are

$$z_1' = z_2, \;\; 1 \leq x \leq 2, z_1(1) = 1/2$$

$$z_2' = z_1^3 - z_1 z_2, \;\; 1 \leq x \leq 2, z_2(1) = -0.2051$$

and solve in the same way

Nonlinear BVP: Shooting method

x_i	z_1	z_2
0	0.5000	-0.2051
0.1000	0.4795	-0.1823
0.2000	0.4613	-0.1626
0.3000	0.4450	-0.1453
0.4000	0.4305	-0.1300
0.5000	0.4175	-0.1164
0.6000	0.4058	-0.1043
0.7000	0.3954	-0.0934
0.8000	0.3861	-0.0835
0.9000	0.3777	-0.0745
1.0000	0.3703	-0.0663

Thanks

Doubts and Suggestions

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MA633L-Numerical Analysis

Lecture 42 : Numerical Differentiation - Shooting Methods

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