

# Natural Cubic Spline Interpolation



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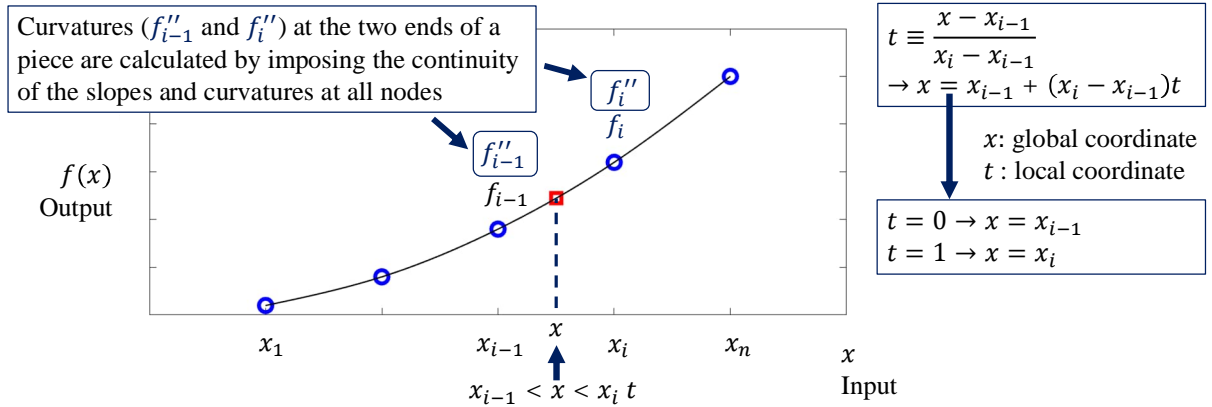
# Natural Cubic Spline

## Formulas

The equation (Eq.1) below is the cubic spline function for interpolating the output  $f$  at an input  $x$  within the range of a piece with endpoints  $x_{i-1}$  and  $x_i$  such that  $x_{i-1} < x < x_i$ . This function uses four known variables  $x_{i-1}, x_i, f_{i-1}, f_i$ , and two unknown variables  $f''_{i-1}, f''_i$ . Even though the two unknown variables  $f''_{i-1}$  and  $f''_i$  are the curvatures at the two endpoints ( $x_i$  and  $x_{i-1}$ ) of the piece, they are calculated (globally) by imposing the continuity of the slopes and curvatures at all data points (nodes). In practice, the  $f''_{i-1}$  and  $f''_i$  are calculated by solving the system of equations in (Eq.2)

$$f(x) = \langle 1 \quad t \quad t^2 \quad t^3 \rangle_{1 \times 4} \begin{bmatrix} 1 & 0 & 0 & 0 \\ -1 & 1 & \frac{-1}{3} & \frac{-1}{6} \\ 0 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & \frac{-1}{6} & \frac{-1}{3} \end{bmatrix}_{4 \times 4} \begin{Bmatrix} f_{i-1} \\ f_i \\ f''_{i-1} (x_i - x_{i-1})^2 \\ f''_i (x_i - x_{i-1})^2 \end{Bmatrix}_{4 \times 1} \quad (1)$$

where  $t$  is related to  $x$  as  $t \equiv \frac{x-x_{i-1}}{x_i-x_{i-1}}$



The two unknown curvatures  $f''_{i-1}$  and  $f''_i$  are calculated by solving a system of equations in (Eq.2) for a set of  $n$  nodes.

$$\begin{bmatrix} 1 & 0 & 0 & \dots & 0 & 0 & 0 \\ \vdots & 0 & a_{i,i-1} & a_{i,i} & a_{i,i+1} & 0 & \vdots \\ 0 & 0 & 0 & \dots & 0 & 0 & 1 \end{bmatrix}_{n \times n} \begin{Bmatrix} f''_1 \\ \vdots \\ f''_i \\ \vdots \\ f''_n \end{Bmatrix}_{n \times 1} = \begin{Bmatrix} 0 \\ \vdots \\ b_i \\ \vdots \\ 0 \end{Bmatrix}_{n \times 1} \quad (2)$$

where  $i$  is index of rows and

$$a_{i,i-1} = \frac{1}{6}(x_i - x_{i-1}); a_{i,i} = \frac{1}{3}(x_{i+1} - x_{i-1}); a_{i,i+1} = \frac{1}{6}(x_{i+1} - x_i); b_i = \frac{f_{i+1}-f_i}{x_{i+1}-x_i} - \frac{f_i-f_{i-1}}{x_i-x_{i-1}}$$

In the system of equations (Eq.2), the first and the last rows are formulated based on the “NATURAL” boundary conditions (zero curvatures) at the left and right end points as

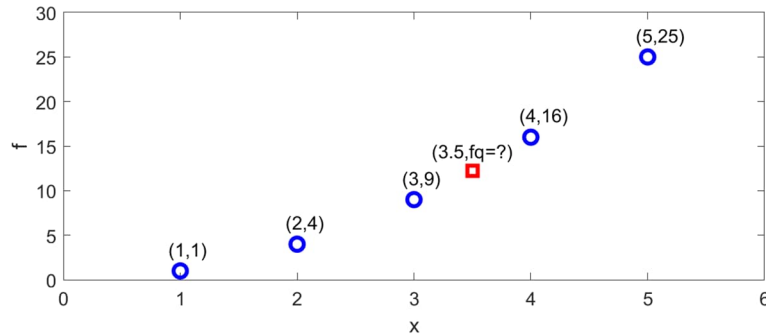
$$\text{Left End: } f''_1 = 0$$

$$\text{Right End: } f''_n = 0$$

### Example

Given: 5 data points:  $(x, f) = (1,1), (2,4), (3,9), (4,16), (5,25)$

Interpolate the output  $f_q$  at input  $x_q = 3.5$  using the natural cubic spline.



### Solution

Step 1: Construct matrix  $[a]_{n \times n}$  and vector  $\{b\}_{n \times 1}$  using Eq. 2

$$[a]_{n \times n} = \begin{bmatrix} 1 & 0 & 0 & \dots & 0 & 0 & 0 \\ \vdots & 0 & a_{i,i-1} & a_{i,i} & a_{i,i+1} & 0 & \vdots \\ 0 & & & & & & \\ 0 & 0 & 0 & \dots & 0 & 0 & 1 \end{bmatrix}_{n \times n}$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0.1667 & 0.6667 & 0.1667 & 0 & 0 \\ 0 & 0.1667 & 0.6667 & 0.1667 & 0 \\ 0 & 0 & 0.1667 & 0.6667 & 0.1667 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}_{5 \times 5}$$

$$\{b\}_{n \times 1} = \begin{Bmatrix} 0 \\ \vdots \\ b_i \\ \vdots \\ 0 \end{Bmatrix}_{n \times 1} = \begin{Bmatrix} 0 \\ 2 \\ 2 \\ 2 \\ 0 \end{Bmatrix}_{5 \times 1}$$

$$a_{i,i-1} = \frac{1}{6}(x_i - x_{i-1}); a_{i,i} = \frac{1}{3}(x_{i+1} - x_{i-1}); a_{i,i+1} = \frac{1}{6}(x_{i+1} - x_i); b_i = \frac{f_{i+1} - f_i}{x_{i+1} - x_i} - \frac{f_i - f_{i-1}}{x_i - x_{i-1}}$$

Step 2: Calculate the vector  $\{f''\}_{n \times 1}$  using Eq. 2

$$\begin{Bmatrix} f_1'' \\ \vdots \\ f_i'' \\ \vdots \\ f_n'' \end{Bmatrix}_{n \times 1} = \begin{bmatrix} 1 & 0 & 0 & \dots & 0 & 0 & 0 \\ \vdots & 0 & a_{i,i-1} & a_{i,i} & a_{i,i+1} & 0 & \vdots \\ 0 & & & & & & \\ 0 & 0 & 0 & \dots & 0 & 0 & 1 \end{bmatrix}_{n \times n}^{-1} \begin{Bmatrix} 0 \\ \vdots \\ b_i \\ \vdots \\ 0 \end{Bmatrix}_{n \times 1}$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0.1667 & 0.6667 & 0.1667 & 0 & 0 \\ 0 & 0.1667 & 0.6667 & 0.1667 & 0 \\ 0 & 0 & 0.1667 & 0.6667 & 0.1667 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}_{5 \times 5}^{-1} \begin{Bmatrix} 0 \\ 2 \\ 2 \\ 2 \\ 0 \end{Bmatrix}_{5 \times 1} = \begin{Bmatrix} 0 \\ 2.5714 \\ 1.7143 \\ 2.5714 \\ 0 \end{Bmatrix}_{5 \times 1}$$

Step 3: Search for the index  $i$  of the right endpoint  $x_i$  of the piece such that  $x_{i-1} < x < x_i$ . The left endpoint of the piece is  $x_{i-1}$ .

```

for i = 2:n % Indix of nodes
    % For interpolation: x(i-1)<xq && xq <= x(i)
    % For extrapolation: xq <= x(1) || xq > x(n)
    if xq <= x(i) || i == n
        break
    end
end
end

```

Step 4: Calculate  $t$ , then construct the vector  $= \langle t \rangle_{1 \times 4}$  in Eq. 1

$$t = \frac{x-x_{i-1}}{x_i-x_{i-1}} = \frac{4.5-4}{4-5} = 0.5$$

$$\langle t \rangle_{1 \times 4} = \langle 1 \quad t \quad t^2 \quad t^3 \rangle_{1 \times 4} = \langle 1 \quad 0.5 \quad 0.5^2 \quad 0.5^3 \rangle_{1 \times 4}$$

Step 5: Calculate  $f_q$  using Eq.1

$$\begin{aligned}
 f(x) &= \langle 1 \quad t \quad t^2 \quad t^3 \rangle_{1 \times 4} \begin{bmatrix} 1 & 0 & 0 & 0 \\ -1 & 1 & \frac{-1}{3} & \frac{-1}{6} \\ 0 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & \frac{-1}{6} & \frac{-1}{3} \end{bmatrix}_{4 \times 4} \begin{Bmatrix} f_{i-1} \\ f_i \\ f_{i-1}''(x_i - x_{i-1})^2 \\ f_i''(x_i - x_{i-1})^2 \end{Bmatrix}_{4 \times 1} \\
 &= \langle 1 \quad 0.5 \quad 0.5^2 \quad 0.5^3 \rangle_{1 \times 4} \begin{bmatrix} 1 & 0 & 0 & 0 \\ -1 & 1 & \frac{-1}{3} & \frac{-1}{6} \\ 0 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & \frac{-1}{6} & \frac{-1}{3} \end{bmatrix}_{4 \times 4} \begin{Bmatrix} 9.0000 \\ 16.0000 \\ 1.7143 \\ 2.5714 \end{Bmatrix}_{4 \times 1} = 12.2321
 \end{aligned}$$

## Code

```

function cm_natural_cubic_spline
% Author: Hejie Lin
% Reference: Compact Math Series: Not-A-Knot Cubic Spline
clear all; clf
% Data
data = [...
    1 , 1;...
    2 , 4;...
    3 , 9;...
    4 , 16;...
    5 , 25];
x = data(:,1);
f = data(:,2);
% New known point
xq = 3.5;
% Construct matrix a and vector b
n = size(data,1); % Number of nodes
a = zeros(n,n);
b = zeros(n,1);
for i = 2:n-1 % Index of the row
    a(i,i-1) = (1/6)*(x(i)-x(i-1));
    a(i,i) = (1/3)*(x(i+1)-x(i-1));
    a(i,i+1) = (1/6)*(x(i+1)-x(i));

```

```

        b(i,1) = (f(i+1)-f(i))/(x(i+1)-x(i))-...
                (f(i-1)-f(i))/(x(i-1)-x(i));
end
% Natural Boundary Conditions
% f''_1 = 0
% f''_n = 0
a(1,1) = 1;
a(n,n) = 1;
% Calculate f''
f2 = inv(a)*b;
% Constant matrix
m_spline = [...
    1, 0, 0, 0;...
   -1, 1, -1/3, -1/6;...
    0, 0, 1/2, 0;...
    0, 0, -1/6, 1/6];
% Search for the piece with endpoints x_{i-1} and x_i
% such that x_{i-1} < x_q <= x_i
for i = 2:n % Index of nodes
    % For interpolation: x(i-1)<x_q && x_q <= x(i)
    % For extrapolation: x_q <= x(1) || x_q > x(n)
    if x_q <= x(i) || i == n
        break
    end
end
end
% Construct vector t and vector f
t = (x_q-x(i-1))/(x(i)-x(i-1));
v_t = [1,t,t^2,t^3];
v_f = [f(i-1);f(i);...
    f2(i-1)*(x(i)-x(i-1))^2;f2(i)*(x(i)-x(i-1))^2];
% Calculate f_q (new unknown point)
f_q = v_t*m_spline*v_f
% Show the results
plot(x,f,'o-k',x_q,f_q,'sr');
end

```

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