

MA378 Chapter 2: Splines

§2.2 (Natural) Cubic Splines

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2.1 Introduction

The **Cubic Spline** is perhaps the most useful and popular interpolating function used in numerical analysis, automotive and aeronautical engineering, computer and film animation, digital photography, financial modelling, and as many other areas as there are human endeavours where continuous processes are modelled by discrete ones.

History

It is generally accepted that (mathematical) splines were first described by Isaac Schoenberg (1903-1990) during WW2. However their physical realisation had been used in the ship-building and aircraft industries prior to that.

2.1 Introduction

For more on cubic splines, see

1. Section 11.4 of “An Introduction to Numerical Analysis”.
2. Lecture 11 of “Afternotes Goes to Graduate School”.

2.1 Introduction

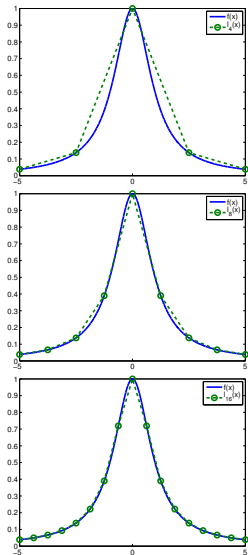
One could argue that the most fundamental short-coming of the linear spline interpolant to f is that they are not “*smooth*”: that is, although

$$l_i(x_i) = l_{i+1}(x_i),$$

it is generally the case that

$$l'_i(x_i) \neq l'_{i+1}(x_i).$$

Also, the interpolating function cannot capture the “*curvature*” of f . (If you think about this last statement, you’ll see that it can be expressed as $l''(x) = 0$ for all $x \in [a, b]$.)



2.2 Definition

Cubic splines try to balance the simplicity of the linear spline approach — by using a low-order polynomial on each interval — with the desire for curvature and more smoothness — by using cubics, and by forcing adjacent ones, and their first and second derivatives, to agree at knot points.

2.2 Definition

Definition 2.1 (Cubic Spline)

Let f be a function that is continuous on $[a, b]$. The *cubic spline interpolant* to f is the continuous function S such that

- (i) for $i = 1, \dots, N$, on each interval $[x_{i-1}, x_i]$ let $S(x) = s_i(x)$, where each of the s_i is a cubic polynomial.
- (ii) $s_i(x_{i-1}) = f(x_{i-1})$ for $i = 1, \dots, N$,
- (iii) $s_i(x_i) = f(x_i)$ for $i = 1, \dots, N$,
- (iv) $s'_i(x_i) = s'_{i+1}(x_i)$ for $i = 1, \dots, N - 1$,
- (v) $s''_i(x_i) = s''_{i+1}(x_i)$ for $i = 1, \dots, N - 1$.

} $4N - 2$
equations

2.2 Definition

So, we have defined the cubic spline S as a function that...

- (a) is a cubic polynomial on each of the n intervals $[x_{i-1}, x_i]$.
That is, it is *piecewise cubic*.
- (b) interpolates f at $N + 1$ points,
- (c) has a continuous first derivatives on $[x_0, x_N]$
- (d) has a continuous second derivatives on $[x_0, x_N]$

2.2 Definition

We know that one can write a cubic as $a_0 + a_1x + a_2x^2 + a_3x^3$. So it takes 4 terms to uniquely define a single cubic. To define the spline we need $4N$ terms. They can be found by solving $4N$ (linearly independent) equations. But the definition only gives $4N - 2$ equations.

So we are short two equations.

2.2 Definition

The “missing” equations can be chosen in a number of ways:

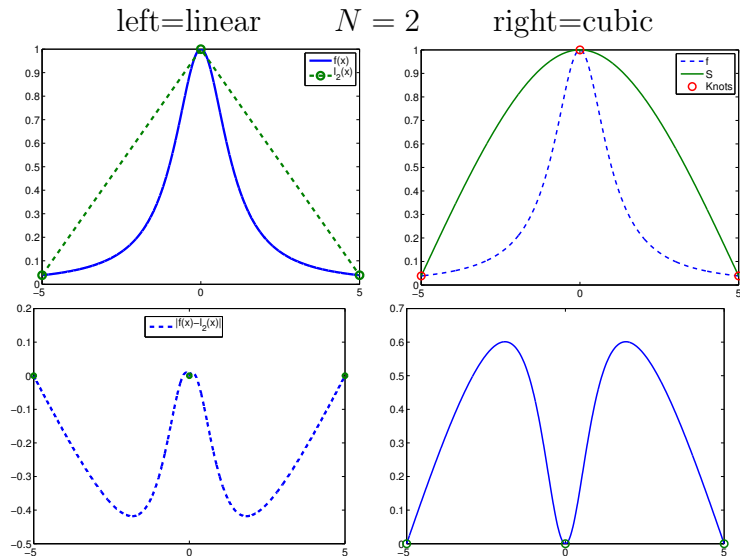
- (i) by setting $S''(x_0) = 0$ and $S''(x_N) = 0$. This is called a *natural* spline, and is the approach we'll take.
- (ii) by setting $S'(x_0) = 0$ and $S'(x_N) = 0$. This is called a *clamped* spline.
- (iii) set $S'(x_0) = S'(x_N)$ and $S''(x_0) = S''(x_N)$. This is the *periodic* spline and is used for interpolating, say, trigonometric functions.
- (iv) only use $N - 2$ components of the spline: s_2, \dots, s_{N-1} . But extend to two end ones so that $s_2(x_0) = f(x_0)$ and $s_{N-1} = f(x_N)$. This is called the *not-a-knot* condition.

2.2 Definition

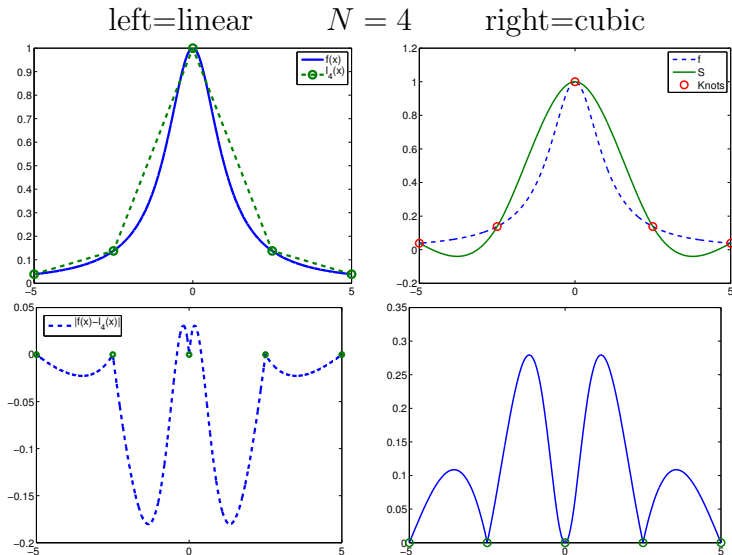
The following figures show the **linear spline** (left) and ***natural cubic spline*** (right), and errors, interpolants to $f(x) = 1/(1 + x^2)$ (with $a = -5$ and $b = 5$ as usual) for various N .

Compared with linear splines, we seem to get significantly better approximation. Moreover, the rate at which the error decreases with respect to h is much faster.

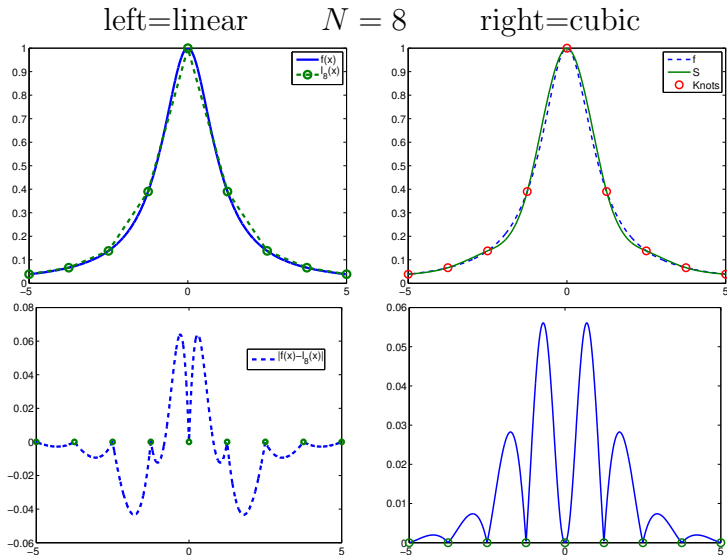
2.2 Definition



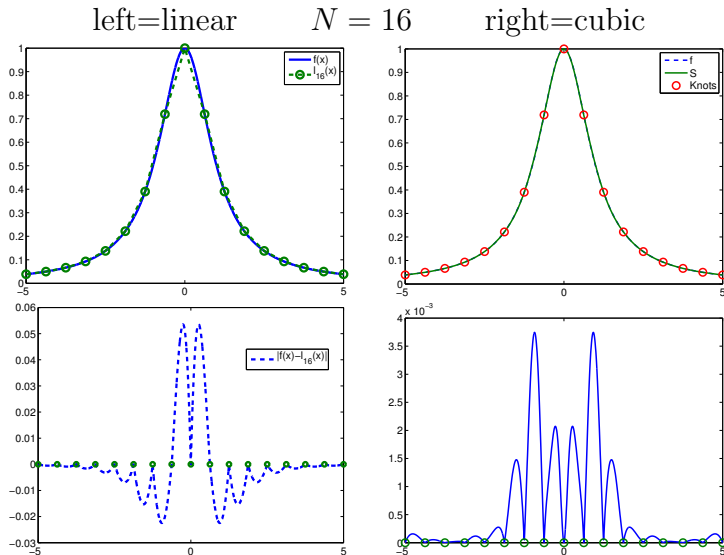
2.2 Definition



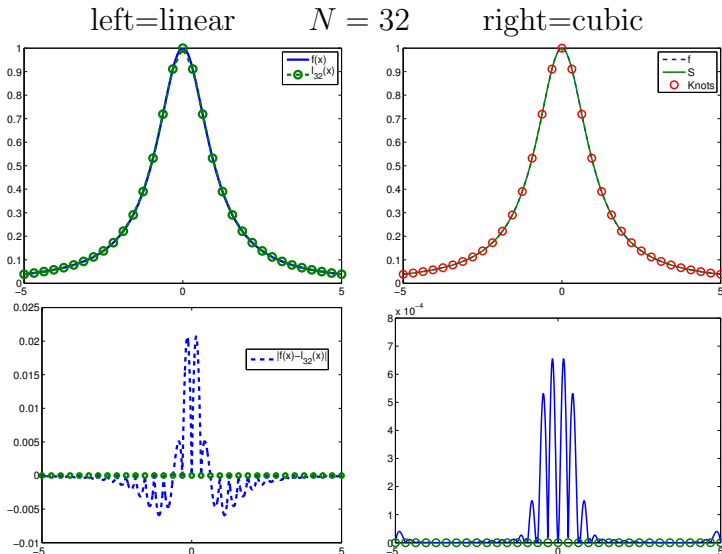
2.2 Definition



2.2 Definition



2.2 Definition



2.3 Constructing Cubic Splines

Some notation:

- ▶ $h = x_i - x_{i-1} = (x_N - x_0)/N$ for all i .
- ▶ $f_i := f(x_i)$.

To construct the spline, first observe that if S is piecewise cubic, then S' is piecewise quadratic, and S'' is piecewise linear.

(i) Let $\sigma_i = S''(x_i)$ for $i = 0, \dots, N$.

We can think of $S''(x)$ as a p.w. linear spline
& $S_i''(x)$ has the formula

$$S_i''(x) = \sigma_{i-1} \frac{x_i - x}{h} + \sigma_i \frac{x - x_{i-1}}{h}$$

Note, however, the σ_i are, as yet, unknown.

2.3 Constructing Cubic Splines

constant of integration.

(ii) Integrate twice:

$$S'_i(x) = -\sigma_{i-1} \frac{(x_i - x)^2}{2h} + \sigma_i \frac{(x - x_{i-1})^2}{2h} + A_i$$

And again: $S_i(x) = \frac{\sigma_{i-1}}{6h} (x_i - x)^3 + \frac{\sigma_i}{6h} (x - x_{i-1})^3 + A_i x + B_i$

We can write $A_i x + B_i$ as

$$\alpha_i (x - x_{i-1}) + \beta_i (x_i - x) = A_i x + B_i$$

We get

$$s_i(x) = \alpha_i(x - x_{i-1}) + \beta_i(x_i - x) + \frac{\sigma_{i-1}}{6h}(x_i - x)^3 + \frac{\sigma_i}{6h}(x - x_{i-1})^3, \quad (1)$$

for $x \in [x_{i-1}, x_i]$.

2.3 Constructing Cubic Splines

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(iii) The α_i and β_i arose as the constants of integration. To find them:

We use that $S_i(x_{i-1}) = f_{i-1}$ & $S_i(x_i) = f_i$

$$S_i(x_{i-1}) = f_{i-1} \Rightarrow h\beta_i + \frac{h^2}{6}\sigma_{i-1} = f_{i-1}$$

Similarly,

$$S_i(x_i) = f_i \Rightarrow h\alpha_i + \frac{h^2}{6}\sigma_i = f_i$$

f_{i-1}, f_i are given. If we know the σ_i , we can solve for α_i, β_i .

2.3 Constructing Cubic Splines

and so, for $i = 1, 2, \dots, N$

$$\alpha_i = \frac{f_i}{h} - \frac{h}{6}\sigma_i, \quad \beta_i = \frac{f_{i-1}}{h} - \frac{h}{6}\sigma_{i-1}. \quad (2)$$

(Note that $\beta_i = \alpha_{i-1}$.)

2.3 Constructing Cubic Splines

- (iv) So, now we “just” need the equations for σ_i . Two of these come from the fact that this is a “natural” cubic spline, with $S''(x_0) = 0$ and $S''(x_N) = 0$, therefore $\sigma_0 = 0$ and $\sigma_N = 0$.

The remaining $N - 1$ equations come from the fact that S' is continuous at x_1, x_2, \dots, x_{N-1} . So we set that

$$s'_i(x_i) = s'_{i+1}(x_i). \quad i=1, \dots, N-1$$

After some work (see exercises...), we can show this means that the system is:

$$\sigma_0 = 0, \quad \sim f''(x_i) \quad (3a)$$

Simpson's Rule \rightarrow

$$\frac{1}{6}(\sigma_{i-1} + 4\sigma_i + \sigma_{i+1}) = \frac{1}{h^2}(f_{i-1} - 2f_i + f_{i+1}) \quad (3b)$$

for $i = 1, \dots, N - 1$,

$$\sigma_N = 0. \quad (3c)$$

2.4 A cubic spline example

Example 2.2

Find the natural cubic spline interpolant to f at the points $x_0 = 0$, $x_1 = 1$, $x_2 = 2$ and $x_3 = 3$ where $f_0 = 0$, $f_1 = 2$, $f_2 = 1$ and $f_3 = 0$.

[We won't do all the details in class, so there are included below]

2.4 A cubic spline example

Solution:

From (1) we see we are looking for $S(x)=$

$$S_1(x) = \alpha_1 x + \beta_1(1-x) + \frac{\sigma_0}{6h}(1-x)^3 + \frac{\sigma_1}{6h}x^3, \quad x \in [0, 1],$$

$$S_2(x) = \alpha_2(x-1) + \beta_2(2-x) + \frac{\sigma_1}{6h}(2-x)^3 + \frac{\sigma_2}{6h}(x-1)^3, \quad x \in [1, 2],$$

$$S_3(x) = \alpha_3(x-x_2) + \beta_3(3-x) + \frac{\sigma_2}{6h}(3-x)^3 + \frac{\sigma_3}{6h}(x-2)^3, \quad x \in [2, 3].$$

11
2

2.4 A cubic spline example

We first solve for the σ_i using (3):

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 4 & 1 & 0 \\ 0 & 1 & 4 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \sigma_0 \\ \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -18 \\ 0 \\ 0 \end{pmatrix}$$

$\frac{1}{h^2} (f_0 - 2f_1 + f_2)$
 $\checkmark = (1) (0 - 2(2) + 1)$
 $= -3$

This gives

$$\sigma_0 = 0, \quad \sigma_1 = -\frac{24}{5}, \quad \sigma_2 = \frac{6}{5}, \quad \sigma_3 = 0.$$

Now use (2) to get

$$\alpha_1 = \frac{14}{5}, \quad \alpha_2 = \frac{4}{5}, \quad \alpha_3 = 0.$$

and

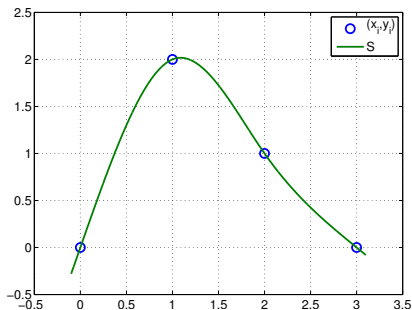
$$\beta_1 = 0, \quad \beta_2 = \frac{14}{5}, \quad \beta_3 = \frac{4}{5}.$$

2.4 A cubic spline example

The answer is

$$S(x) = \begin{cases} \frac{14}{5}x - \frac{4}{5}x^3, & x \in [0, 1], \\ \frac{4}{5}(x-1) + \frac{14}{5}(2-x) - \frac{4}{5}(2-x)^3 + \frac{1}{5}(x-1)^3, & x \in [1, 2], \\ \frac{4}{5}(3-x) + \frac{1}{5}(3-x)^3. & x \in [2, 3]. \end{cases}$$

This is shown below.



2.5 Error Estimates

We state the following error estimates without proof. You don't need to know these, or be able to prove them. But you should be able to use them if required.

Theorem 2.3

If $f \in C^4[a, b]$ and S is its cubic spline interpolant on $N + 1$ equally spaced points, then

$$\|f - S\|_{\infty} \leq \frac{5}{384} M_4 h^4,$$

$$\|f' - S'\|_{\infty} \leq \frac{1}{24} M_4 h^3,$$

$$\|f'' - S''\|_{\infty} \leq \frac{3}{8} M_4 h^2,$$

where $M_4 = \|f^{(iv)}\|_{\infty}$.

Here
 $M_4 = \|f^{(iv)}\|_{\infty}$.
 h^4 is
very important.

2.5 Error Estimates

Example 2.4

Give an upper bound on the error for the cubic spline interpolant to $f = e^x$ on the interval $[-1, 1]$ with $N = 10$ mesh points.

Since $f(x) = e^x$, then $f^{(4)}(x) = e^x$.

So $m_4 = \|f^{(4)}\|_\infty = e \approx 2.718$.

$N = 10$, so $h = \frac{x_N - x_0}{N} = \frac{1 - (-1)}{10} = 0.2$

So,
$$\|f - S\|_\infty \leq \frac{5}{384} (m_4) h^4 = \frac{5}{384} (2.718) (0.2)^4$$
$$\approx 5.6631 \times 10^{-5}$$

2.5 Error Estimates

Example 2.5

What is the smallest value of N that you must take to ensure that, if interpolating $f(x) = e^x$ on N equally sized intervals, the error is less than 10^{-8} ? How does this compare with a linear spline interpolation (see corresponding example for linear splines), *again on $[-1, 1]$.*

$$\text{We want } \|f - S\|_{\infty} \leq \frac{5}{384} M_4 h^4 \leq 10^{-8}$$

Using $M_4 = 2.718$ we'll find ...

$$h \leq 0.02306. \quad \text{since } h = \frac{2}{N},$$

we get $N \geq 86.7$.

Take $N = 87$.

For linear splines we'd
need to take
 $N \geq 10,000$

Recall the minimum energy property of linear splines. There is an analogous result for natural cubic splines.

Theorem 2.6

Let u be any function that interpolates f at ω^N , and is such that $u \in H^2(x_0, x_N)$. Then

$$\|S''\|_2 \leq \|u''\|_2.$$

The proof is not hard - it is analogous to the proof of Theorem 2.1.9.

Note: Cubic Splines are not local, which is why we must solve a linear system...

2.6 Exercises

Exercise 2.1

When deducing the system of equations for the natural cubic spline, we showed how to construct the formulation given in (1) and the relationship between σ_i , α_i and β_i in (2). Now carefully show to deduce the system (3).

Exercise 2.2

(For students who did MA385). Write the equations in (3) as a matrix-vector equation $A\sigma = \mathbf{b}$, where A is an $n \times n$ matrix. Show that A is nonsingular, and hence that the system has a unique solution.

Exercise 2.3

Find the natural cubic spline interpolant to $f(x) = \sin(\pi x/2)$ at the nodes $\{x_i\}_{i=0}^3 = \{0, 1, 2, 3\}$. Calculate value of the interpolant at $x = 2.5$. What is the error at this point?

2.6 Exercises

Exercise 2.4

Take $f(x) = \ln(x)$, $x_0 = 1$, $x_N = 2$. What value of N would you have to take to ensure that $|\ln(x) - S(x)| \leq 10^{-4}$ for all $x \in [1, 2]$?

Exercise 2.5

Suppose that S is a natural cubic spline on $[0, 2]$ with

$$S(x) = \begin{cases} -3x + 2(1-x) + a(1-x)^3 + \frac{2}{3}x^3, & x \in [0, 1), \\ b(2-x) + c(2-x)^3 + d(x-1)^3, & x \in [1, 2]. \end{cases}$$

Find a , b , c , and d .

2.6 Exercises

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