

## **Spline Method of Interpolation**

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After reading this chapter, you should be able to:

1. *interpolate data using spline interpolation, and*
2. *understand why spline interpolation is important.*

### **What is interpolation?**

Many times, data is given only at discrete points such as  $(x_0, y_0)$ ,  $(x_1, y_1)$ ,  $\dots, (x_{n-1}, y_{n-1})$ ,  $(x_n, y_n)$ . So, how then does one find the value of  $y$  at any other value of  $x$ ? Well, a continuous function  $f(x)$  may be used to represent the  $n+1$  data values with  $f(x)$  passing through the  $n+1$  points (Figure 1). Then one can find the value of  $y$  at any other value of  $x$ . This is called *interpolation*.

Of course, if  $x$  falls outside the range of  $x$  for which the data is given, it is no longer interpolation but instead is called *extrapolation*.

So what kind of function  $f(x)$  should one choose? A polynomial is a common choice for an interpolating function because polynomials are easy to

- (A) evaluate,
- (B) differentiate, and
- (C) integrate

relative to other choices such as a trigonometric and exponential series.

Polynomial interpolation involves finding a polynomial of order  $n$  that passes through the  $n+1$  points. Several methods to obtain such a polynomial include the direct method, Newton's divided difference polynomial method and the Lagrangian interpolation method.

So is the spline method yet another method of obtaining this  $n^{\text{th}}$  order polynomial. .... NO! Actually, when  $n$  becomes large, in many cases, one may get oscillatory behavior in the resulting polynomial. This was shown by Runge when he interpolated data based on a simple function of

$$y = \frac{1}{1 + 25x^2}$$

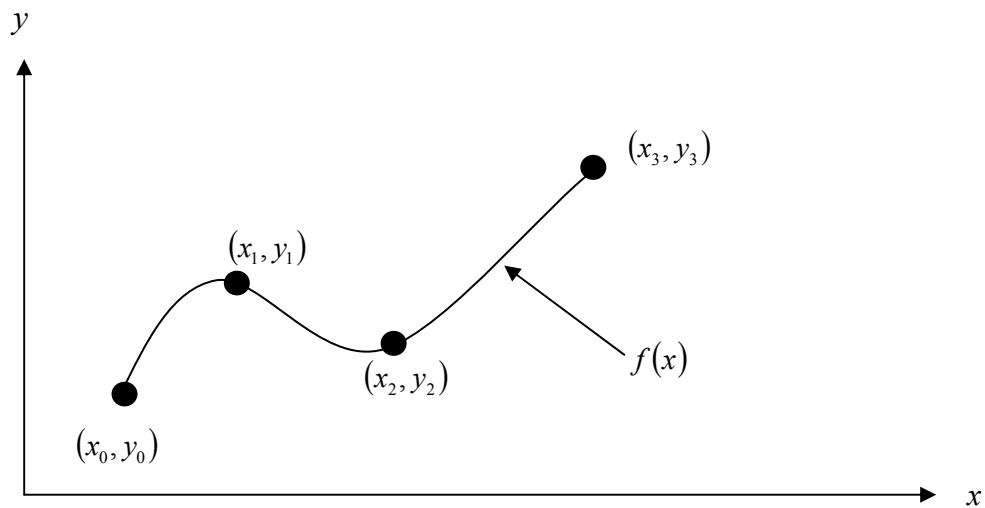
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on an interval of  $[-1, 1]$ . For example, take six equidistantly spaced points in  $[-1, 1]$  and find  $y$  at these points as given in Table 1.



**Figure 1** Interpolation of discrete data.

**Table 1** Six equidistantly spaced points in  $[-1, 1]$ .

$x$	$y = \frac{1}{1 + 25x^2}$
-1.0	0.038461
-0.6	0.1
-0.2	0.5
0.2	0.5

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0.6	0.1
1.0	0.038461

Now through these six points, one can pass a fifth order polynomial

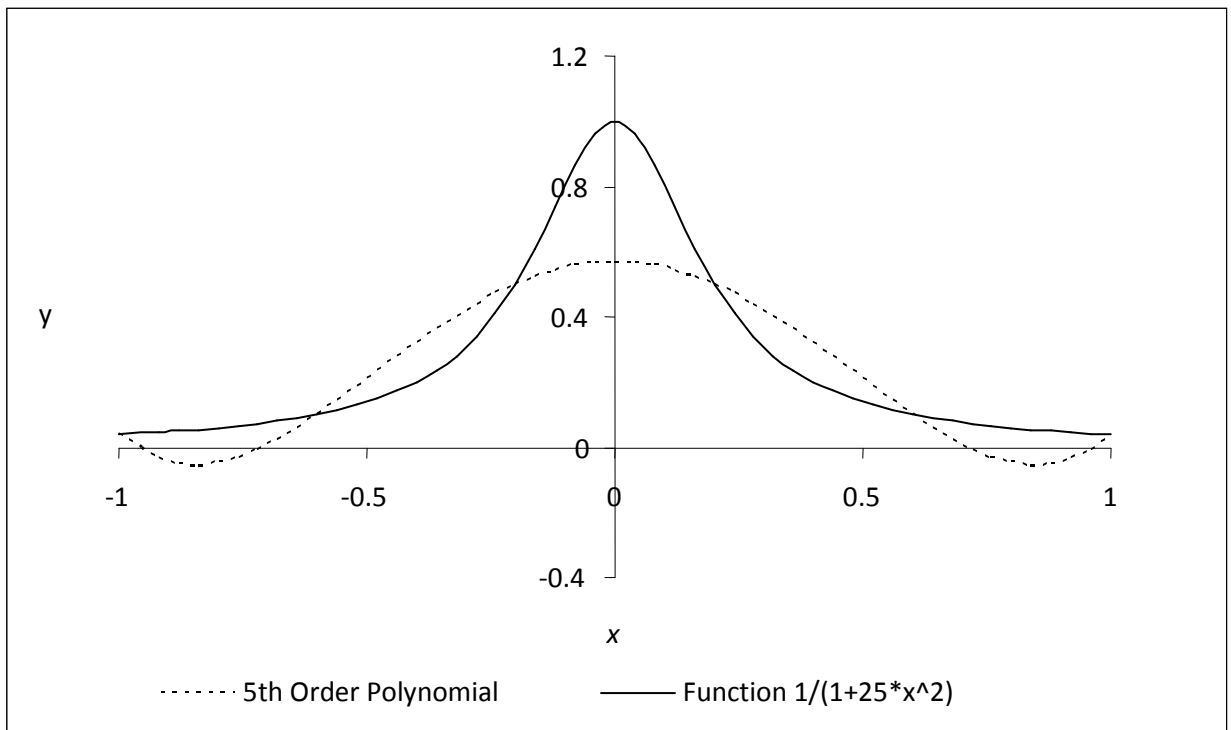
$$f_5(x) = 3.1378 \times 10^{-11} x^5 + 1.2019 x^4 - 3.3651 \times 10^{-11} x^3 - 1.7308 x^2 + 1.0004 \times 10^{-11} x + 5.6731 \times 10^{-1},$$

$$-1 \leq x \leq 1$$

through the six data points. On plotting the fifth order polynomial (Figure 2) and the original function, one can see that the two do not match well. One may consider choosing more points in the interval  $[-1, 1]$  to get a better match, but it diverges even more (see Figure 3), where 20 equidistant points were chosen in the interval  $[-1, 1]$  to draw a 19th order polynomial. In fact, Runge found that as the order of the polynomial becomes infinite, the polynomial diverges in the interval of  $-1 < x < -0.726$  and  $0.726 < x < 1$ .

So what is the answer to using information from more data points, but at the same time keeping the function true to the data behavior? The answer is in spline interpolation. The most common spline interpolations used are linear, quadratic, and cubic splines.





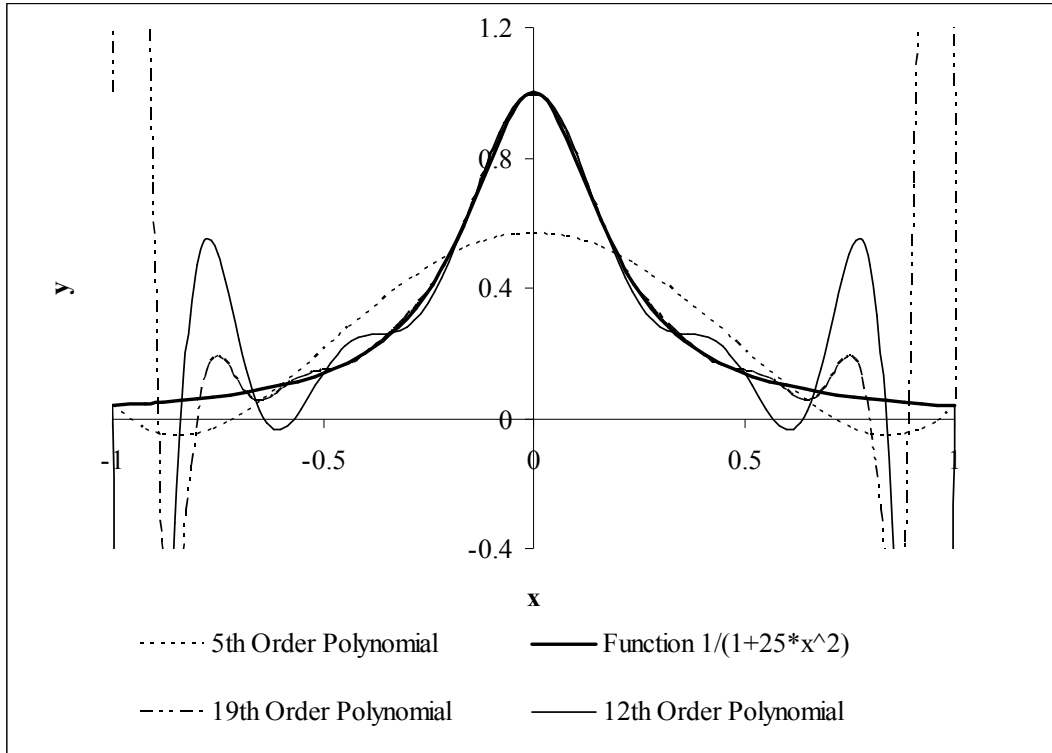
**Figure 2** 5th order polynomial interpolation with six equidistant points.

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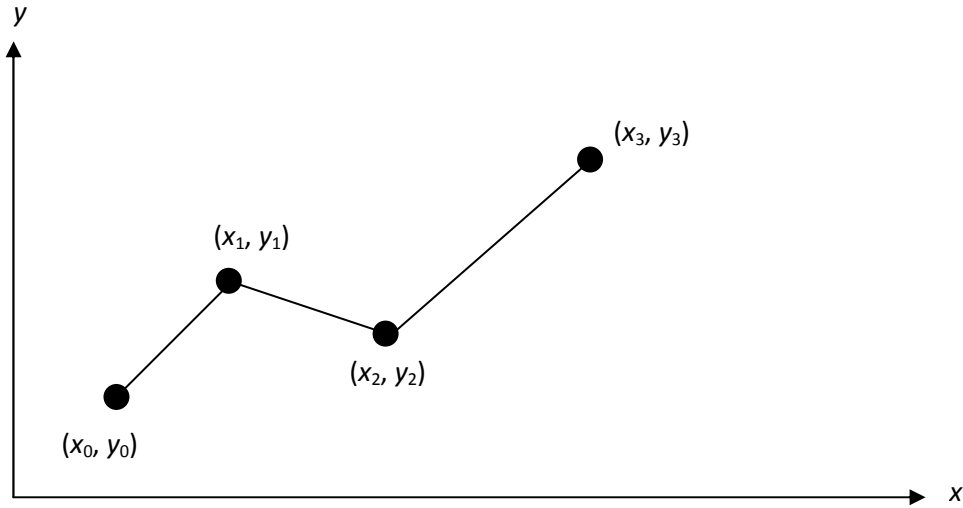


**Figure 3** Higher order polynomial interpolation is a bad idea.

### Linear Spline Interpolation

Given  $(x_0, y_0), (x_1, y_1), \dots, (x_{n-1}, y_{n-1}), (x_n, y_n)$ , fit linear splines (Figure 4) to the data. This simply involves forming the consecutive data through straight lines. So if the above data is given in an ascending order, the linear splines are given by  $y_i = f(x_i)$ .





**Figure 4** Linear splines.

$$\begin{aligned}
 f(x) &= f(x_0) + \frac{f(x_1) - f(x_0)}{x_1 - x_0}(x - x_0), & x_0 \leq x \leq x_1 \\
 &= f(x_1) + \frac{f(x_2) - f(x_1)}{x_2 - x_1}(x - x_1), & x_1 \leq x \leq x_2 \\
 &\cdot \\
 &\cdot \\
 &\cdot \\
 &= f(x_{n-1}) + \frac{f(x_n) - f(x_{n-1})}{x_n - x_{n-1}}(x - x_{n-1}), & x_{n-1} \leq x \leq x_n
 \end{aligned}$$

Note the terms of

$$\frac{f(x_i) - f(x_{i-1})}{x_i - x_{i-1}}$$

in the above function are simply slopes between  $x_{i-1}$  and  $x_i$ .

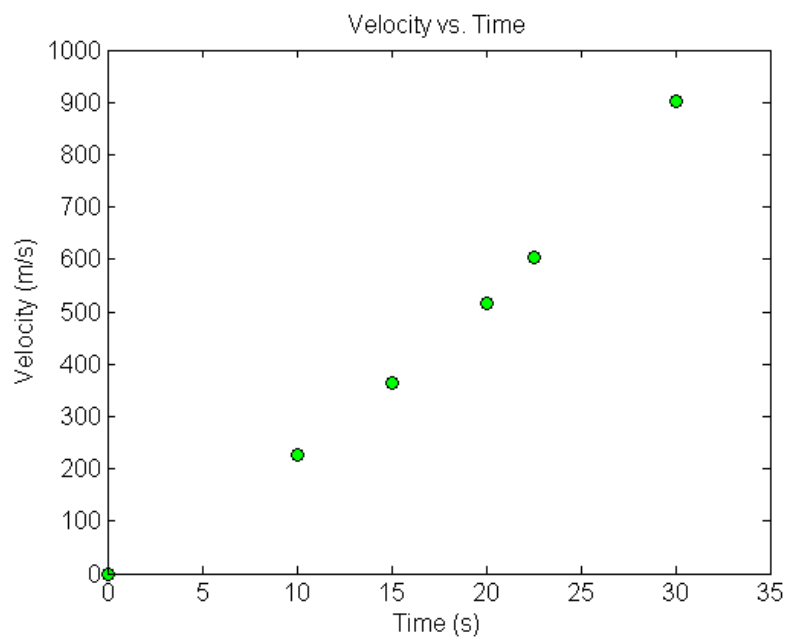


### Example 1

The upward velocity of a rocket is given as a function of time in Table 2 (Figure 5).

**Table 2** Velocity as a function of time.

$t$ (s)	$v(t)$ (m/s)
0	0
10	227.04
15	362.78
20	517.35
22.5	602.97
30	901.67



**Figure 5** Graph of velocity vs. time data for the rocket

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example.

Determine the value of the velocity at  $t = 16$  seconds using linear splines.

### Solution

Since we want to evaluate the velocity at  $t = 16$ , and we are using linear splines, we need to choose the two data points closest to  $t = 16$  that also bracket  $t = 16$  to evaluate it. The two points are  $t_0 = 15$  and  $t_1 = 20$ .

Then

$$t_0 = 15, \quad v(t_0) = 362.78$$

$$t_1 = 20, \quad v(t_1) = 517.35$$

gives

$$\begin{aligned} v(t) &= v(t_0) + \frac{v(t_1) - v(t_0)}{t_1 - t_0} (t - t_0) \\ &= 362.78 + \frac{517.35 - 362.78}{20 - 15} (t - 15) \\ &= 362.78 + 30.913(t - 15), \quad 15 \leq t \leq 20 \end{aligned}$$

At  $t = 16$ ,

$$\begin{aligned} v(16) &= 362.78 + 30.913(16 - 15) \\ &= 393.7 \text{ m/s} \end{aligned}$$

Linear spline interpolation is no different from linear polynomial interpolation. Linear splines still use data only from the two consecutive data points. Also at the interior points of the data, the slope changes abruptly. This means that the first derivative is not continuous at these points. So how do we improve on this? We can do so by using quadratic splines.





## Quadratic Splines

In these splines, a quadratic polynomial approximates the data between two consecutive data points. Given  $(x_0, y_0), (x_1, y_1), \dots, (x_{n-1}, y_{n-1}), (x_n, y_n)$ , fit quadratic splines through the data. The splines are given by

$$\begin{aligned} f(x) &= a_1x^2 + b_1x + c_1, & x_0 \leq x \leq x_1 \\ &= a_2x^2 + b_2x + c_2, & x_1 \leq x \leq x_2 \\ &\cdot \\ &\cdot \\ &\cdot \\ &= a_nx^2 + b_nx + c_n, & x_{n-1} \leq x \leq x_n \end{aligned}$$

So how does one find the coefficients of these quadratic splines? There are  $3n$  such coefficients

$$a_i, i = 1, 2, \dots, n$$

$$b_i, i = 1, 2, \dots, n$$

$$c_i, i = 1, 2, \dots, n$$

To find  $3n$  unknowns, one needs to set up  $3n$  equations and then simultaneously solve them. These  $3n$  equations are found as follows.

1. Each quadratic spline goes through two consecutive data points

$$a_1x_0^2 + b_1x_0 + c_1 = f(x_0)$$

$$a_1x_1^2 + b_1x_1 + c_1 = f(x_1)$$

·

·



$$a_i x_{i-1}^2 + b_i x_{i-1} + c_i = f(x_{i-1})$$

$$a_i x_i^2 + b_i x_i + c_i = f(x_i)$$

$$a_n x_{n-1}^2 + b_n x_{n-1} + c_n = f(x_{n-1})$$

$$a_n x_n^2 + b_n x_n + c_n = f(x_n)$$

This condition gives  $2n$  equations as there are  $n$  quadratic splines going through two consecutive data points.

2. The first derivatives of two quadratic splines are continuous at the interior points. For example, the derivative of the first spline

$$a_1 x^2 + b_1 x + c_1$$

is

$$2a_1 x + b_1$$

The derivative of the second spline

$$a_2 x^2 + b_2 x + c_2$$

is

$$2a_2 x + b_2$$

and the two are equal at  $x = x_1$  giving

$$2a_1 x_1 + b_1 = 2a_2 x_1 + b_2$$

$$2a_1 x_1 + b_1 - 2a_2 x_1 - b_2 = 0$$

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Similarly at the other interior points,

$$2a_2x_2 + b_2 - 2a_3x_2 - b_3 = 0$$

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$$2a_ix_i + b_i - 2a_{i+1}x_i - b_{i+1} = 0$$

.

.

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$$2a_{n-1}x_{n-1} + b_{n-1} - 2a_nx_{n-1} - b_n = 0$$

Since there are  $(n - 1)$  interior points, we have  $(n - 1)$  such equations. So far, the total number of equations is  $(2n) + (n - 1) = (3n - 1)$  equations. We still then need one more equation.

We can assume that the first spline is linear, that is

$$a_1 = 0$$

This gives us  $3n$  equations and  $3n$  unknowns. These can be solved by a number of techniques used to solve simultaneous linear equations.

## Example 2

The upward velocity of a rocket is given as a function of time as



**Table 3** Velocity as a function of time.

$t$ (s)	$v(t)$ (m/s)
0	0
10	227.04
15	362.78
20	517.35
22.5	602.97
30	901.67

- Determine the value of the velocity at  $t = 16$  seconds using quadratic splines.
- Using the quadratic splines as velocity functions, find the distance covered by the rocket from  $t = 11$ s to  $t = 16$ s.
- Using the quadratic splines as velocity functions, find the acceleration of the rocket at  $t = 16$ s.

### Solution

- Since there are six data points, five quadratic splines pass through them.

$$\begin{aligned}v(t) &= a_1t^2 + b_1t + c_1, \quad 0 \leq t \leq 10 \\ &= a_2t^2 + b_2t + c_2, \quad 10 \leq t \leq 15 \\ &= a_3t^2 + b_3t + c_3, \quad 15 \leq t \leq 20 \\ &= a_4t^2 + b_4t + c_4, \quad 20 \leq t \leq 22.5 \\ &= a_5t^2 + b_5t + c_5, \quad 22.5 \leq t \leq 30\end{aligned}$$

The equations are found as follows.

- Each quadratic spline passes through two consecutive data points.

$$a_1t^2 + b_1t + c_1 \text{ passes through } t = 0 \text{ and } t = 10.$$



$$a_1(0)^2 + b_1(0) + c_1 = 0 \quad (1)$$

$$a_1(10)^2 + b_1(10) + c_1 = 227.04 \quad (2)$$

$a_2t^2 + b_2t + c_2$  passes through  $t = 10$  and  $t = 15$ .

$$a_2(10)^2 + b_2(10) + c_2 = 227.04 \quad (3)$$

$$a_2(15)^2 + b_2(15) + c_2 = 362.78 \quad (4)$$

$a_3t^2 + b_3t + c_3$  passes through  $t = 15$  and  $t = 20$ .

$$a_3(15)^2 + b_3(15) + c_3 = 362.78 \quad (5)$$

$$a_3(20)^2 + b_3(20) + c_3 = 517.35 \quad (6)$$

$a_4t^2 + b_4t + c_4$  passes through  $t = 20$  and  $t = 22.5$ .

$$a_4(20)^2 + b_4(20) + c_4 = 517.35 \quad (7)$$

$$a_4(22.5)^2 + b_4(22.5) + c_4 = 602.97 \quad (8)$$

$a_5t^2 + b_5t + c_5$  passes through  $t = 22.5$  and  $t = 30$ .

$$a_5(22.5)^2 + b_5(22.5) + c_5 = 602.97 \quad (9)$$



$$a_5(30)^2 + b_5(30) + c_5 = 901.67$$

(10)

2. Quadratic splines have continuous derivatives at the interior data points.

At  $t = 10$

$$2a_1(10) + b_1 - 2a_2(10) - b_2 = 0$$

(11)

At  $t = 15$

$$2a_2(15) + b_2 - 2a_3(15) - b_3 = 0$$

(12)

At  $t = 20$

$$2a_3(20) + b_3 - 2a_4(20) - b_4 = 0$$

(13)

At  $t = 22.5$

$$2a_4(22.5) + b_4 - 2a_5(22.5) - b_5 = 0$$

(14)

3. Assuming the first spline  $a_1t^2 + b_1t + c_1$  is linear,

$$a_1 = 0$$

(15)

Combining Equation (1) –(15) in matrix form gives



$$\begin{bmatrix}
 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 100 & 10 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 100 & 10 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 225 & 15 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 225 & 15 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 400 & 20 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 400 & 20 & 1 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 506.25 & 22.5 & 1 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 506.25 & 22.5 & 1 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 900 & 30 & 1 & 0 \\
 20 & 1 & 0 & -20 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 30 & 1 & 0 & -30 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 40 & 1 & 0 & -40 & -1 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 45 & 1 & 0 & -45 & -1 & 0 \\
 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
 \end{bmatrix}
 \begin{bmatrix}
 a_1 \\
 b_1 \\
 c_1 \\
 a_2 \\
 b_2 \\
 c_2 \\
 a_3 \\
 b_3 \\
 c_3 \\
 a_4 \\
 b_4 \\
 c_4 \\
 a_5 \\
 b_5 \\
 c_5
 \end{bmatrix}
 =
 \begin{bmatrix}
 0 \\
 227.04 \\
 227.04 \\
 362.78 \\
 362.78 \\
 517.35 \\
 517.35 \\
 602.97 \\
 602.97 \\
 901.67 \\
 0 \\
 0 \\
 0 \\
 0 \\
 0
 \end{bmatrix}$$

Solving the above 15 equations give the 15 unknowns as

$i$	$a_i$	$b_i$	$c_i$
1	0	22.704	0
2	0.8888	4.928	88.88
3	-0.1356	35.66	-141.61
4	1.6048	-33.956	554.55
5	0.20889	28.86	-152.13

Therefore, the splines are given by

$$\begin{aligned}
 v(t) &= 22.704t, & 0 \leq t \leq 10 \\
 &= 0.8888t^2 + 4.928t + 88.88, & 10 \leq t \leq 15 \\
 &= -0.1356t^2 + 35.66t - 141.61, & 15 \leq t \leq 20
 \end{aligned}$$

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$$= 1.6048t^2 - 33.956t + 554.55, \quad 20 \leq t \leq 22.5$$

$$= 0.20889t^2 + 28.86t - 152.13, \quad 22.5 \leq t \leq 30$$

At  $t = 16$ s

$$\begin{aligned} v(16) &= -0.1356(16)^2 + 35.66(16) - 141.61 \\ &= 394.24 \text{ m/s} \end{aligned}$$

b) The distance covered by the rocket between 11 and 16 seconds can be calculated as

$$s(16) - s(11) = \int_{11}^{16} v(t) dt$$

But since the splines are valid over different ranges, we need to break the integral accordingly as

$$v(t) = 0.8888t^2 + 4.928t + 88.88, \quad 10 \leq t \leq 15$$

$$= -0.1356t^2 + 35.66t - 141.61, \quad 15 \leq t \leq 20$$

$$\int_{11}^{16} v(t) dt = \int_{11}^{15} v(t) dt + \int_{15}^{16} v(t) dt$$

$$s(16) - s(11) = \int_{11}^{15} (0.8888t^2 + 4.928t + 88.88) dt + \int_{15}^{16} (-0.1356t^2 + 35.66t - 141.61) dt$$

$$\begin{aligned} &= \left[ 0.8888 \frac{t^3}{3} + 4.928 \frac{t^2}{2} + 88.88t \right]_{11}^{15} \\ &\quad + \left[ -0.1356 \frac{t^3}{3} + 35.66 \frac{t^2}{2} - 141.61t \right]_{15}^{16} \end{aligned}$$

$$= 1217.35 + 378.53$$

$$= 1595.9 \text{ m}$$

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c) What is the acceleration at  $t = 16$  ?

$$a(16) = \left. \frac{d}{dt} v(t) \right|_{t=16}$$

$$a(t) = \frac{d}{dt} v(t) = \frac{d}{dt} (-0.1356t^2 + 35.66t - 141.61)$$

$$= -0.2712t + 35.66, \quad 15 \leq t \leq 20$$

$$a(16) = -0.2712(16) + 35.66$$

$$= 31.321 \text{m/s}^2$$

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