

## Chapter 08.03

# Runge-Kutta 2nd Order Method for Ordinary Differential Equations

*After reading this chapter, you should be able to:*

1. *understand the Runge-Kutta 2nd order method for ordinary differential equations and how to use it to solve problems.*

### What is the Runge-Kutta 2nd order method?

The Runge-Kutta 2nd order method is a numerical technique used to solve an ordinary differential equation of the form

$$\frac{dy}{dx} = f(x, y), y(0) = y_0$$

Only first order ordinary differential equations can be solved by using the Runge-Kutta 2nd order method. In other sections, we will discuss how the Euler and Runge-Kutta methods are used to solve higher order ordinary differential equations or coupled (simultaneous) differential equations.

How does one write a first order differential equation in the above form?

### Example 1

Rewrite

$$\frac{dy}{dx} + 2y = 1.3e^{-x}, y(0) = 5$$

in

$$\frac{dy}{dx} = f(x, y), y(0) = y_0 \text{ form.}$$

### Solution

$$\frac{dy}{dx} + 2y = 1.3e^{-x}, y(0) = 5$$

$$\frac{dy}{dx} = 1.3e^{-x} - 2y, y(0) = 5$$

In this case

$$f(x, y) = 1.3e^{-x} - 2y$$

**Example 2**

Rewrite

$$e^y \frac{dy}{dx} + x^2 y^2 = 2 \sin(3x), \quad y(0) = 5$$

in

$$\frac{dy}{dx} = f(x, y), \quad y(0) = y_0 \text{ form.}$$

**Solution**

$$e^y \frac{dy}{dx} + x^2 y^2 = 2 \sin(3x), \quad y(0) = 5$$

$$\frac{dy}{dx} = \frac{2 \sin(3x) - x^2 y^2}{e^y}, \quad y(0) = 5$$

In this case

$$f(x, y) = \frac{2 \sin(3x) - x^2 y^2}{e^y}$$

**Runge-Kutta 2<sup>nd</sup> order method**

Euler's method is given by

$$y_{i+1} = y_i + f(x_i, y_i)h \quad (1)$$

where

$$x_0 = 0$$

$$y_0 = y(x_0)$$

$$h = x_{i+1} - x_i$$

To understand the Runge-Kutta 2<sup>nd</sup> order method, we need to derive Euler's method from the Taylor series.

$$\begin{aligned} y_{i+1} &= y_i + \left. \frac{dy}{dx} \right|_{x_i, y_i} (x_{i+1} - x_i) + \frac{1}{2!} \left. \frac{d^2 y}{dx^2} \right|_{x_i, y_i} (x_{i+1} - x_i)^2 + \frac{1}{3!} \left. \frac{d^3 y}{dx^3} \right|_{x_i, y_i} (x_{i+1} - x_i)^3 + \dots \\ &= y_i + f(x_i, y_i)(x_{i+1} - x_i) + \frac{1}{2!} f'(x_i, y_i)(x_{i+1} - x_i)^2 + \frac{1}{3!} f''(x_i, y_i)(x_{i+1} - x_i)^3 + \dots \quad (2) \end{aligned}$$

As you can see the first two terms of the Taylor series

$$y_{i+1} = y_i + f(x_i, y_i)h$$

are Euler's method and hence can be considered to be the Runge-Kutta 1<sup>st</sup> order method.

The true error in the approximation is given by

$$E_i = \frac{f'(x_i, y_i)}{2!} h^2 + \frac{f''(x_i, y_i)}{3!} h^3 + \dots \quad (3)$$

So what would a 2<sup>nd</sup> order method formula look like. It would include one more term of the Taylor series as follows.

$$y_{i+1} = y_i + f(x_i, y_i)h + \frac{1}{2!} f'(x_i, y_i)h^2 \quad (4)$$

Let us take a generic example of a first order ordinary differential equation

$$\frac{dy}{dx} = e^{-2x} - 3y, y(0) = 5$$

$$f(x, y) = e^{-2x} - 3y$$

Now since  $y$  is a function of  $x$ ,

$$\begin{aligned} f'(x, y) &= \frac{\partial f(x, y)}{\partial x} + \frac{\partial f(x, y)}{\partial y} \frac{dy}{dx} \\ &= \frac{\partial}{\partial x}(e^{-2x} - 3y) + \frac{\partial}{\partial y}[(e^{-2x} - 3y)](e^{-2x} - 3y) \\ &= -2e^{-2x} + (-3)(e^{-2x} - 3y) \\ &= -5e^{-2x} + 9y \end{aligned} \quad (5)$$

The 2nd order formula for the above example would be

$$\begin{aligned} y_{i+1} &= y_i + f(x_i, y_i)h + \frac{1}{2!} f'(x_i, y_i)h^2 \\ &= y_i + (e^{-2x_i} - 3y_i)h + \frac{1}{2!}(-5e^{-2x_i} + 9y_i)h^2 \end{aligned}$$

However, we already see the difficulty of having to find  $f'(x, y)$  in the above method. What Runge and Kutta did was write the 2nd order method as

$$y_{i+1} = y_i + (a_1 k_1 + a_2 k_2)h \quad (6)$$

where

$$\begin{aligned} k_1 &= f(x_i, y_i) \\ k_2 &= f(x_i + p_1 h, y_i + q_{11} k_1 h) \end{aligned} \quad (7)$$

This form allows one to take advantage of the 2nd order method without having to calculate  $f'(x, y)$ .

So how do we find the unknowns  $a_1$ ,  $a_2$ ,  $p_1$  and  $q_{11}$ . Without proof (see Appendix for proof), equating Equation (4) and (6), gives three equations.

$$a_1 + a_2 = 1$$

$$a_2 p_1 = \frac{1}{2}$$

$$a_2 q_{11} = \frac{1}{2}$$

Since we have 3 equations and 4 unknowns, we can assume the value of one of the unknowns. The other three will then be determined from the three equations. Generally the value of  $a_2$  is chosen to evaluate the other three constants. The three values generally used

for  $a_2$  are  $\frac{1}{2}$ , 1 and  $\frac{2}{3}$ , and are known as Heun's Method, the midpoint method and

Ralston's method, respectively.

Heun's Method

Here  $a_2 = \frac{1}{2}$  is chosen, giving

$$a_1 = \frac{1}{2}$$

$$p_1 = 1$$

$$q_{11} = 1$$

resulting in

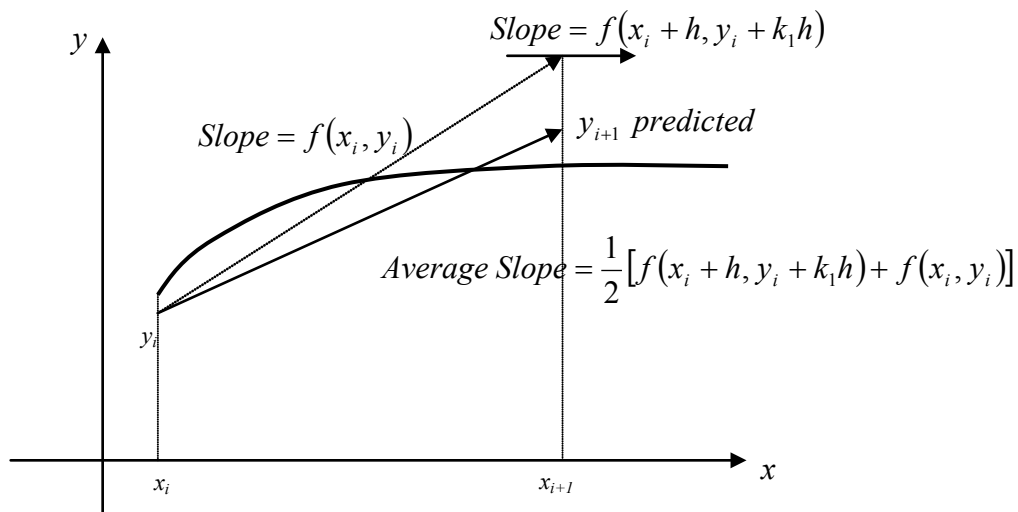
$$y_{i+1} = y_i + \left( \frac{1}{2}k_1 + \frac{1}{2}k_2 \right)h \quad (8)$$

where

$$k_1 = f(x_i, y_i) \quad (9a)$$

$$k_2 = f(x_i + h, y_i + k_1h) \quad (9b)$$

This method is graphically explained in Figure 1.



**Figure 1** Runge-Kutta 2nd order method (Heun's method).

Midpoint Method

Here  $a_2 = 1$  is chosen, giving

$$a_1 = 0$$

$$p_1 = \frac{1}{2}$$

$$q_{11} = \frac{1}{2}$$

resulting in

$$y_{i+1} = y_i + k_2h \quad (10)$$

where

$$k_1 = f(x_i, y_i) \quad (11a)$$

$$k_2 = f\left(x_i + \frac{1}{2}h, y_i + \frac{1}{2}k_1h\right) \quad (11b)$$

Ralston's Method

Here  $a_2 = \frac{2}{3}$  is chosen, giving

$$a_1 = \frac{1}{3}$$

$$p_1 = \frac{3}{4}$$

$$q_{11} = \frac{3}{4}$$

resulting in

$$y_{i+1} = y_i + \left(\frac{1}{3}k_1 + \frac{2}{3}k_2\right)h \quad (12)$$

where

$$k_1 = f(x_i, y_i) \quad (13a)$$

$$k_2 = f\left(x_i + \frac{3}{4}h, y_i + \frac{3}{4}k_1h\right) \quad (13b)$$

**Example 3**

The concentration of salt  $x$  in a home made soap maker is given as a function of time by

$$\frac{dx}{dt} = 37.5 - 3.5x$$

At the initial time,  $t = 0$ , the salt concentration in the tank is 50 g/L. Using Runge-Kutta 2<sup>nd</sup> order method and a step size of  $h = 1.5$  min, what is the salt concentration after 3 minutes?

**Solution**

$$\frac{dx}{dt} = 37.5 - 3.5x$$

$$f(t, x) = 37.5 - 3.5x$$

Per Heun's method

$$x_{i+1} = x_i + \left(\frac{1}{2}k_1 + \frac{1}{2}k_2\right)h$$

$$k_1 = f(t_i, x_i)$$

$$k_2 = f(t_i + h, x_i + k_1h)$$

For  $i = 0$ ,  $t_0 = 0$ ,  $x_0 = 50$

$$k_1 = f(t_0, x_0)$$

$$= f(0, 50)$$

$$= 37.5 - 3.5(50)$$

$$= -137.5$$

$$\begin{aligned}
 k_2 &= f(t_0 + h, x_0 + k_1 h) \\
 &= f(0 + 1.5, 50 + (-137.5)1.5) \\
 &= f(1.5, -156.25) \\
 &= 37.5 - 3.5(-156.25) \\
 &= 584.38 \\
 x_1 &= x_0 + \left( \frac{1}{2}k_1 + \frac{1}{2}k_2 \right)h \\
 &= 50 + \left( \frac{1}{2}(-137.5) + \frac{1}{2}(584.38) \right)1.5 \\
 &= 50 + (223.44)1.5 \\
 &= 385.16 \text{ g/L}
 \end{aligned}$$

$x_1$  is the approximate concentration of salt at

$$t = t_1 = t_0 + h = 0 + 1.5 = 1.5 \text{ min}$$

$$x(1.5) \approx x_1 = 385.16 \text{ g/L}$$

For  $i = 1$ ,  $t_1 = t_0 + h = 0 + 1.5 = 1.5$ ,  $x_1 = 385.16$

$$\begin{aligned}
 k_1 &= f(t_1, x_1) \\
 &= f(1.5, 385.16) \\
 &= 37.5 - 3.5(385.16) \\
 &= -1310.5
 \end{aligned}$$

$$\begin{aligned}
 k_2 &= f(t_1 + h, x_1 + k_1 h) \\
 &= f(1.5 + 1.5, 385.16 + (-1310.5)1.5) \\
 &= f(3, -1580.6) \\
 &= 37.5 - 3.5(-1580.6) \\
 &= 5569.8
 \end{aligned}$$

$$\begin{aligned}
 x_2 &= x_1 + \left( \frac{1}{2}k_1 + \frac{1}{2}k_2 \right)h \\
 &= 385.16 + \left( \frac{1}{2}(-1310.5) + \frac{1}{2}(5569.8) \right)1.5 \\
 &= 385.16 + (2129.6)1.5 \\
 &= 3579.6 \text{ g/L} \\
 x(3) &\approx x_2 = 3579.7 \text{ g/L}
 \end{aligned}$$

$x_2$  is the approximate concentration of salt at

$$t = t_2 = t_1 + h = 1.5 + 1.5 = 3 \text{ min}$$

$$x(3) \approx x_2 = 3579.7 \text{ g/L}$$

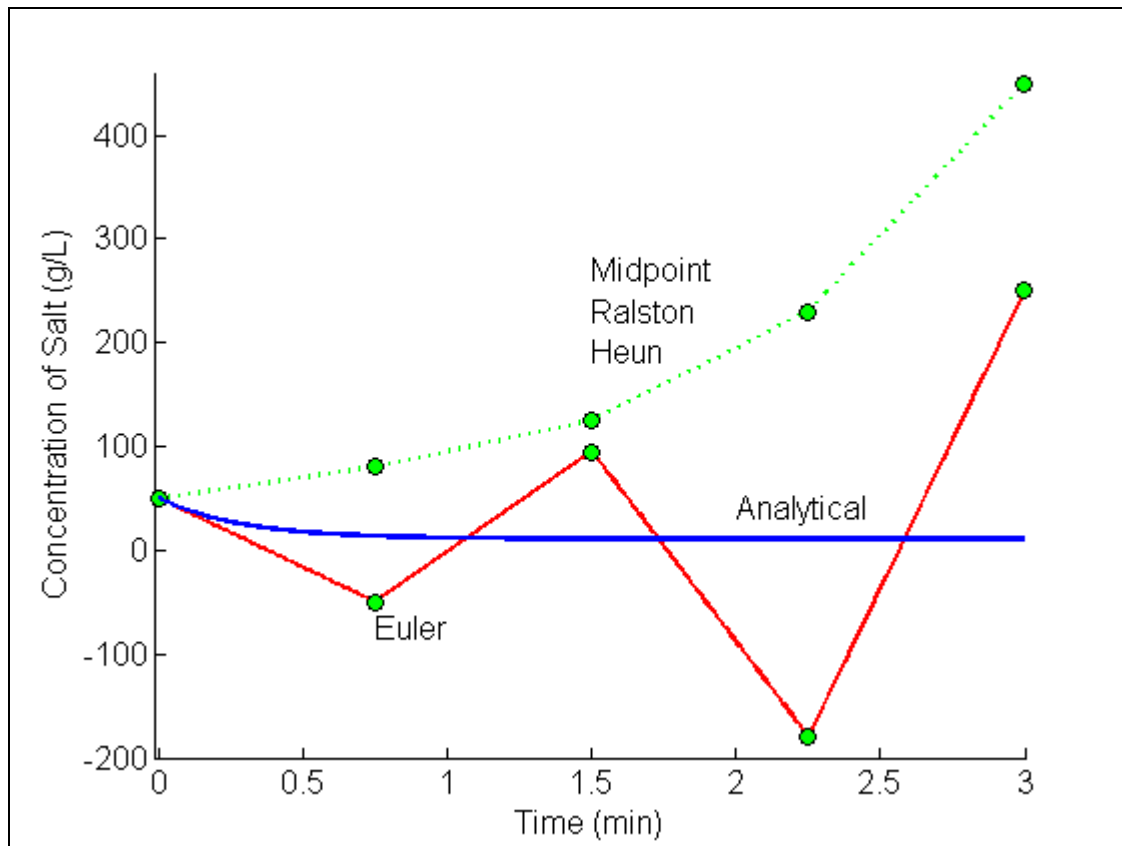
The results from Heun's method are compared with exact results in Figure 2.

The exact solution of the ordinary differential equation is given by

$$x(t) = 10.714 + 39.286e^{-3.5t}$$

The solution to this nonlinear equation at  $t = 3$  min is

$$x(3) = 10.715 \text{ g/L}$$

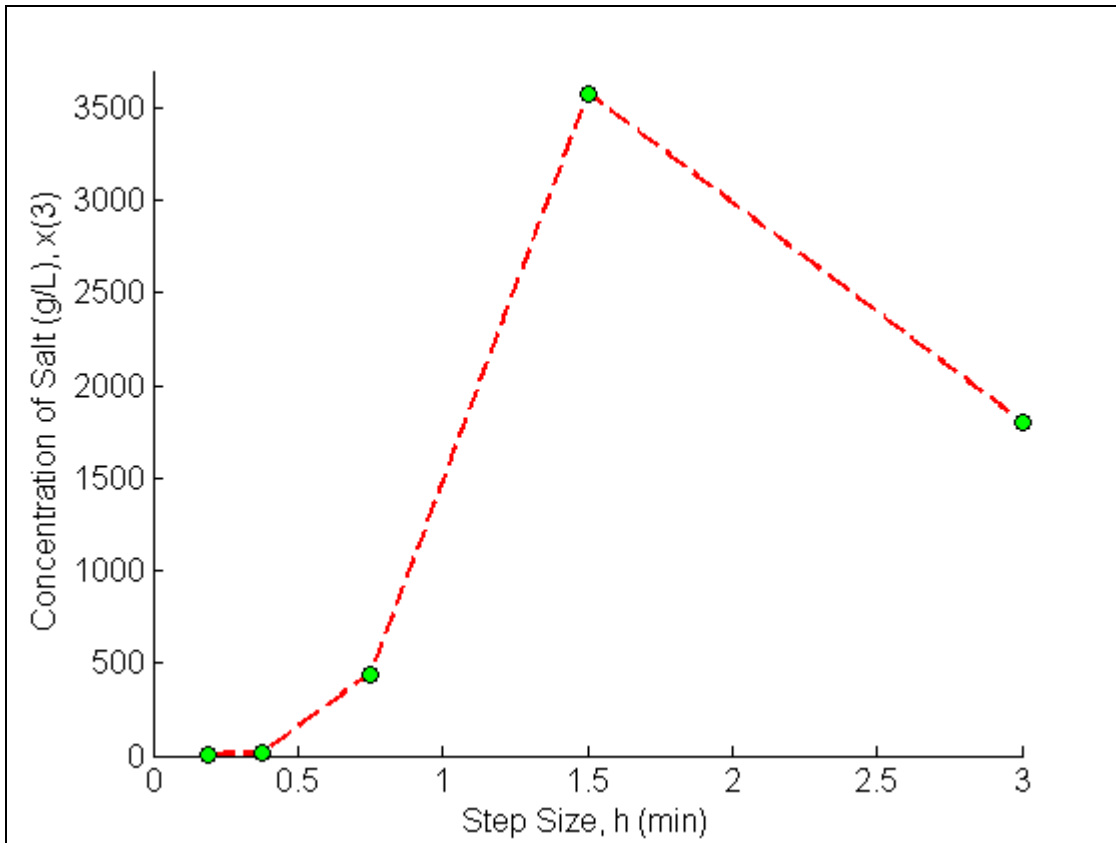


**Figure 2** Heun's method results for different step sizes.

Using smaller step size would increase the accuracy of the result as given in Table 1 and Figure 3.

**Table 1** Effect of step size for Heun's method.

Step Size, $h$	$x(3)$	$E_t$	$ \epsilon_t $ %
3	1803.1	-1792.4	16727
1.5	3579.6	-3568.9	33306
0.75	442.05	-431.34	4025.4
0.375	11.038	-0.32231	3.0079
0.1875	10.718	-0.0024979	0.023311



**Figure 3** Effect of step size in Heun's method.

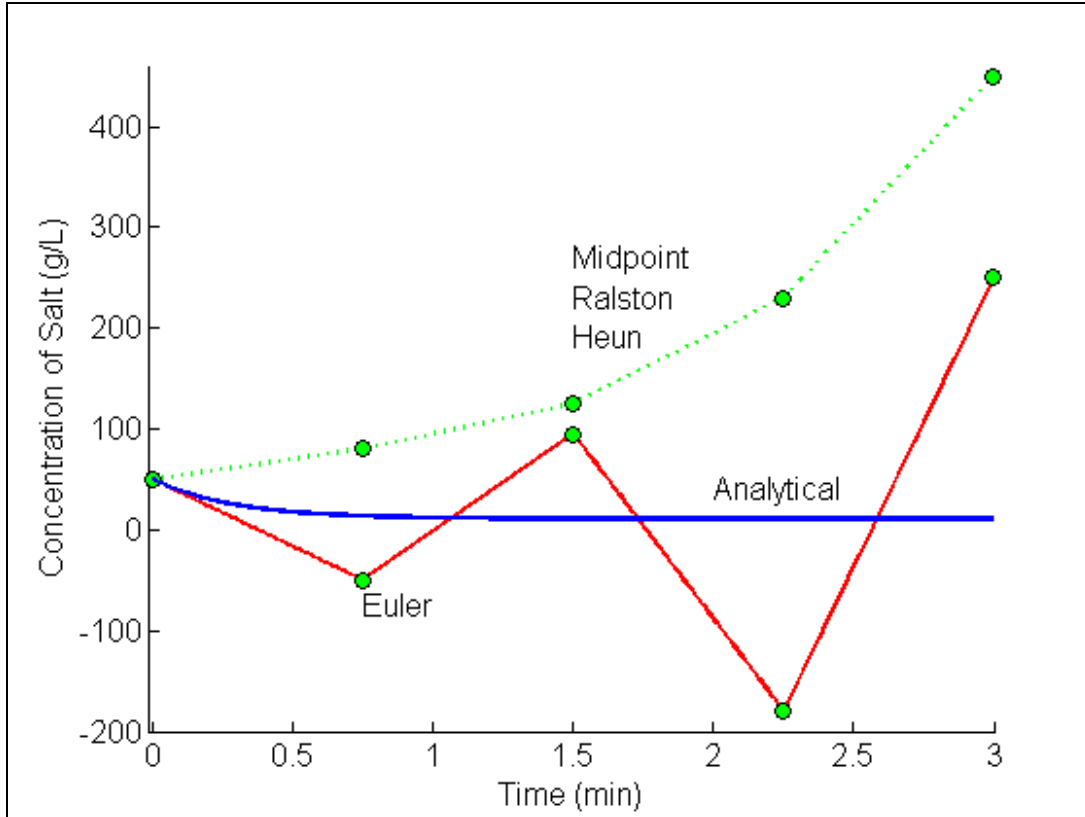
In Table 2, the Euler's method and Runge-Kutta 2<sup>nd</sup> order method results are shown as a function of step size.

**Table 2** Comparison of Euler and the Runge-Kutta methods.

Step size, $h$	$x(3)$			
	Euler	Heun	Midpoint	Ralston
3	-362.50	1803.1	1803.1	1803.1
1.5	720.31	3579.6	3579.6	3579.6
0.75	284.65	442.05	442.05	442.05
0.375	10.718	11.038	11.038	11.038
0.1875	10.714	10.718	10.718	10.718



Figure 4 shows the comparison of Euler and Runge-Kutta methods over time.



**Figure 4** Comparison of Euler and Runge Kutta methods with exact results over time.

**How do these three methods compare with results obtained if we found  $f'(x, y)$  directly?**

Of course, we know that since we are including the first three terms in the series, if the solution is a polynomial of order two or less (that is, quadratic, linear or constant), any of the three methods are exact. But for any other case the results will be different.

Let us take the example of

$$\frac{dy}{dx} = e^{-2x} - 3y, y(0) = 5.$$

If we directly find  $f'(x, y)$ , the first three terms of the Taylor series gives

$$y_{i+1} = y_i + f(x_i, y_i)h + \frac{1}{2!}f'(x_i, y_i)h^2$$

where

$$f(x, y) = e^{-2x} - 3y$$

$$f'(x, y) = -5e^{-2x} + 9y$$

For a step size of  $h = 0.2$ , using Heun's method, we find

$$y(0.6) = 1.0930$$

The exact solution

$$y(x) = e^{-2x} + 4e^{-3x}$$

gives

$$\begin{aligned} y(0.6) &= e^{-2(0.6)} + 4e^{-3(0.6)} \\ &= 0.96239 \end{aligned}$$

Then the absolute relative true error is

$$\begin{aligned} |\epsilon_t| &= \left| \frac{0.96239 - 1.0930}{0.96239} \right| \times 100 \\ &= 13.571\% \end{aligned}$$

For the same problem, the results from Euler's method and the three Runge-Kutta methods are given in Table 3.

**Table 3** Comparison of Euler's and Runge-Kutta 2nd order methods

	y(0.6)					
	Exact	Euler	Direct 2nd	Heun	Midpoint	Ralston
Value	0.96239	0.4955	1.0930	1.1012	1.0974	1.0994
$ \epsilon_t $ %		48.514	13.571	14.423	14.029	14.236

## Appendix A

### How do we get the 2nd order Runge-Kutta method equations?

We wrote the 2nd order Runge-Kutta equations without proof to solve

$$\frac{dy}{dx} = f(x, y), \quad y(0) = y_0 \quad (\text{A.1})$$

as

$$y_{i+1} = y_i + (a_1 k_1 + a_2 k_2)h \quad (\text{A.2})$$

where

$$k_1 = f(x_i, y_i) \quad (\text{A.3a})$$

$$k_2 = f(x_i + p_1 h, y_i + q_{11} k_1 h) \quad (\text{A.3b})$$

and

$$\begin{aligned} a_1 + a_2 &= 1 \\ a_2 p_2 &= \frac{1}{2} \\ a_2 q_{11} &= \frac{1}{2} \end{aligned} \quad (\text{A.4})$$

The advantage of using 2nd order Runge-Kutta method equations is based on not having to find the derivative of  $f(x, y)$  symbolically in the ordinary differential equation

So how do we get the above three Equations (A.4)? This is the question that is answered in this Appendix.

Writing out the first three terms of Taylor series are

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$$y_{i+1} = y_i + \left. \frac{dy}{dx} \right|_{x_i, y_i} h + \frac{1}{2!} \left. \frac{d^2 y}{dx^2} \right|_{x_i, y_i} h^2 + O(h^3) \quad (\text{A.5})$$

where

$$h = x_{i+1} - x_i$$

Since

$$\frac{dy}{dx} = f(x, y)$$

we can rewrite the Taylor series as

$$y_{i+1} = y_i + f(x_i, y_i)h + \frac{1}{2!} f'(x_i, y_i)h^2 + O(h^3) \quad (\text{A.6})$$

Now

$$f'(x, y) = \frac{\partial f(x, y)}{\partial x} + \frac{\partial f(x, y)}{\partial y} \frac{dy}{dx}. \quad (\text{A.7})$$

Hence

$$\begin{aligned} y_{i+1} &= y_i + f(x_i, y_i)h + \frac{1}{2!} \left( \left. \frac{\partial f}{\partial x} \right|_{x_i, y_i} + \left. \frac{\partial f}{\partial y} \right|_{x_i, y_i} \times \left. \frac{dy}{dx} \right|_{x_i, y_i} \right) h^2 + O(h^3) \\ &= y_i + f(x_i, y_i)h + \frac{1}{2} \left. \frac{\partial f}{\partial x} \right|_{x_i, y_i} h^2 + \frac{1}{2} \left. \frac{\partial f}{\partial y} \right|_{x_i, y_i} f(x_i, y_i)h^2 + O(h^3) \end{aligned} \quad (\text{A.8})$$

Now the term used in the Runge-Kutta 2nd order method for  $k_2$  can be written as a Taylor series of two variables with the first three terms as

$$\begin{aligned} k_2 &= f(x_i + p_1 h, y_i + q_{11} k_1 h) \\ &= f(x_i, y_i) + p_1 h \left. \frac{\partial f}{\partial x} \right|_{x_i, y_i} + q_{11} k_1 h \left. \frac{\partial f}{\partial y} \right|_{x_i, y_i} + O(h^2) \end{aligned} \quad (\text{A.9})$$

Hence

$$\begin{aligned} y_{i+1} &= y_i + (a_1 k_1 + a_2 k_2)h \\ &= y_i + \left( a_1 f(x_i, y_i) + a_2 \left\{ f(x_i, y_i) + p_1 h \left. \frac{\partial f}{\partial x} \right|_{x_i, y_i} + q_{11} k_1 h \left. \frac{\partial f}{\partial y} \right|_{x_i, y_i} + O(h^2) \right\} \right) h \\ &= y_i + (a_1 + a_2) h f(x_i, y_i) + a_2 p_1 h^2 \left. \frac{\partial f}{\partial x} \right|_{x_i, y_i} + a_2 q_{11} f(x_i, y_i) h^2 \left. \frac{\partial f}{\partial y} \right|_{x_i, y_i} + O(h^3) \end{aligned} \quad (\text{A.10})$$

Equating the terms in Equation (A.8) and Equation (A.10), we get

$$a_1 + a_2 = 1$$

$$a_2 p_1 = \frac{1}{2}$$

$$a_2 q_{11} = \frac{1}{2}$$

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**ORDINARY DIFFERENTIAL EQUATIONS**

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Topic	Runge 2nd Order Method for Ordinary Differential Equations
Summary	Textbook notes on Runge 2nd order method for ODE
Major	Chemical Engineering
Authors	Autar Kaw
Last Revised	November 8, 2012
Web Site	<a href="http://numericalmethods.eng.usf.edu">http://numericalmethods.eng.usf.edu</a>

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