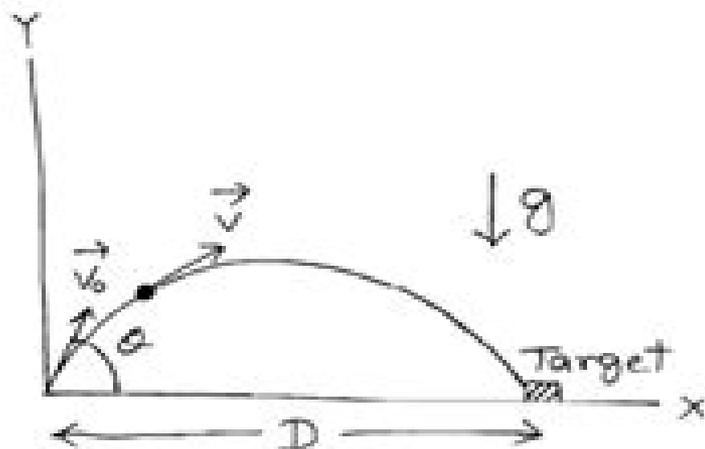


Consider the motion of a projectile in earth's gravitational field. The projectile of mass  $m$  is launched from the origin in a direction making an angle  $\theta$  with the horizontal so as to hit a target placed at a distance  $D$ . There is a frictional force due to the air resistance acting on the projectile, which is opposite to the velocity direction and proportional to the square velocity. The equation

of motion from the Newton's Laws is:

$$M \left( \hat{i} \frac{d^2x}{dt^2} + \hat{j} \frac{d^2y}{dt^2} \right) = -Mg \hat{j} - \kappa v^2 \hat{v}$$

The following parameters are given:  $g = 10 \text{ m/sec}^2$ ,  $D = 1 \text{ Km}$ , and the air friction parameter  $\alpha = \kappa / M = 0.001 \text{ m}^{-1}$ . If air friction is zero, then the analytical solution is known from elementary physics (formula given below), which you can use to check the results from your computer code. Draw appropriate graphs to discuss all key results.



- Write a computer code to solve the boundary value problem by using the shooting method.
- Determine the initial speed  $v_0$  as a function of  $\theta$  ( $0 < \theta < \pi/2$ ) so that it hits the target.
- What is the minimum value of  $v_0$  needed for the projectile to hit the target and what is the corresponding  $\theta$ ?
- Repeat the above for  $\alpha = 0.002 \text{ m}^{-1}$  and  $\alpha = 0.005 \text{ m}^{-1}$ .

Note: I suggested above some values for  $\alpha$ . Determine appropriate values from your own numerical simulations so that you can see the effect of friction on motion. If friction is too high, the particle may not reach the target. If it is too low, you obtain results close to the analytical solution from elementary physics, viz.,  $v_0 = \sqrt{Dg / \sin 2\theta}$ .

**Numerical Method:** Choose one of the following methods to solve the differential equations. Use a constant step size, just small enough that you can reproduce the analytical result for the initial speed  $v_0$  accurate to within 0.001 % for the case of zero air resistance and  $\theta = 45^\circ$ .

- The fourth-order Runge Kutta Method to carry out the entire integration.

# Projectile Motion Using Runge Kutta Methods

**Claus Siebe, José Luis Macías, Gerardo  
J. Aguirre-Díaz**

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