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## Chapter 7 : Gravitation (Solved Examples & Exercises)

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### Notes

Step-by-step solutions · NCERT Examples 7.1–7.8 and Exercises 7.1–7.21 · Class 11 Physics

### Part A — NCERT Solved Examples

#### Example 7.1

**Question:** Let the speed of the planet at the perihelion P in Fig. 7.1(a) be  $v_P$  and the Sun-planet distance SP be  $r_P$ . Relate  $\{r_P, v_P\}$  to the corresponding quantities at the aphelion  $\{r_A, v_A\}$ . Will the planet take equal times to traverse BAC and CPB?

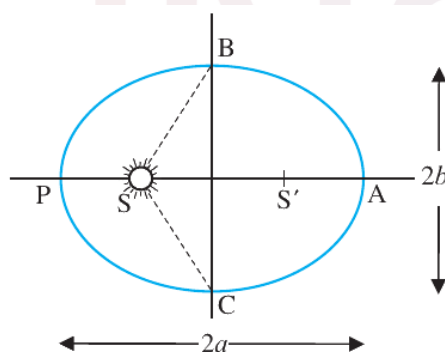


Fig. 7.1(a)

**Solution:** The magnitude of the angular momentum at P is  $L_P = m_P r_P v_P$ , since  $\vec{r}_P$  and  $\vec{v}_P$  are mutually perpendicular. Similarly,  $L_A = m_P r_A v_A$ . From angular momentum conservation:

$$m_P r_P v_P = m_P r_A v_A \quad \Rightarrow \quad \frac{v_P}{v_A} = \frac{r_A}{r_P}$$

Since  $r_A > r_P$ ,  $v_P > v_A$ .

The area SBAC bounded by the ellipse and the radius vectors SB and SC is larger than SBPC. From Kepler's second law, equal areas are swept in equal times. Hence the planet takes a **longer time to traverse BAC than CPB**.

#### Example 7.2

**Question:** Three equal masses of  $m$  kg each are fixed at the vertices of an equilateral triangle ABC. (a) What is the force acting on a mass  $2m$  placed at the centroid G of the triangle? (b) What is the force if the mass at the vertex A is doubled? Take  $AG = BG = CG = 1$  m.

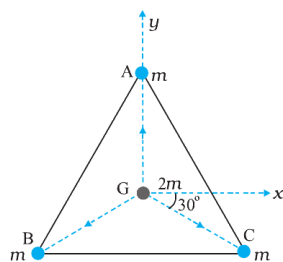


Fig. 7.5

**Solution:**

(a) The angle between GC and the positive x-axis is  $30^\circ$ , and so is the angle between GB and the negative x-axis.

$$\begin{aligned}\vec{F}_{GA} &= \frac{Gm(2m)}{1} \hat{j} \\ \vec{F}_{GB} &= \frac{Gm(2m)}{1} (-\hat{i} \cos 30^\circ - \hat{j} \sin 30^\circ) \\ \vec{F}_{GC} &= \frac{Gm(2m)}{1} (+\hat{i} \cos 30^\circ - \hat{j} \sin 30^\circ)\end{aligned}$$

By superposition:

$$\vec{F}_R = 2Gm^2 \hat{j} + 2Gm^2 (-\hat{i} \cos 30^\circ - \hat{j} \sin 30^\circ) + 2Gm^2 (\hat{i} \cos 30^\circ - \hat{j} \sin 30^\circ) = 0$$

By symmetry, one also expects the resultant force to be zero.

(b) If the mass at A is doubled:

$$\begin{aligned}\vec{F}'_{GA} &= \frac{G(2m)(2m)}{1} \hat{j} = 4Gm^2 \hat{j}, \quad \vec{F}'_{GB} = \vec{F}_{GB}, \quad \vec{F}'_{GC} = \vec{F}_{GC} \\ \vec{F}'_R &= \vec{F}'_{GA} + \vec{F}'_{GB} + \vec{F}'_{GC} = 2Gm^2 \hat{j}\end{aligned}$$

**Answer:** (a) zero (b)  $2Gm^2 \hat{j}$  N

### Example 7.3

**Question:** Find the potential energy of a system of four particles placed at the vertices of a square of side  $l$ . Also obtain the potential at the centre of the square.

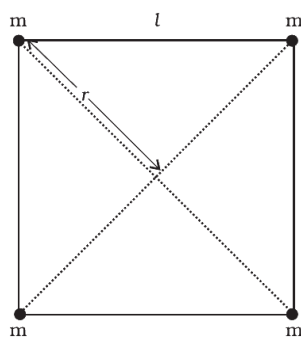


Fig. 7.9

**Solution:** There are four mass pairs at distance  $l$  and two diagonal pairs at distance  $\sqrt{2} l$ :

$$W = -4 \frac{Gm^2}{l} - 2 \frac{Gm^2}{\sqrt{2} l} = -\frac{2Gm^2}{l} \left( 2 + \frac{1}{\sqrt{2}} \right) = -5.41 \frac{Gm^2}{l}$$

The gravitational potential at the centre of the square ( $r = \sqrt{2} l/2$ ) is

$$U = -4 \frac{Gm}{\sqrt{2} l/2} = -4\sqrt{2} \frac{Gm}{l}$$

### Example 7.4

**Question:** Two uniform solid spheres of equal radii  $R$ , but mass  $M$  and  $4M$ , have a centre to centre separation  $6R$ , as shown in Fig. 7.10. The two spheres are held fixed. A projectile of mass  $m$  is projected from the surface of the sphere of mass  $M$  directly towards the centre of the second sphere. Obtain an expression for the minimum speed  $v$  of the projectile so that it reaches the surface of the second sphere.

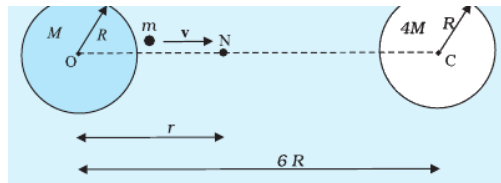


Fig. 7.10

**Solution:** The projectile is acted on by two opposing gravitational forces. The neutral point  $N$  is where they cancel. If  $ON = r$ :

$$\frac{GMm}{r^2} = \frac{4GMm}{(6R - r)^2} \Rightarrow (6R - r)^2 = 4r^2 \Rightarrow 6R - r = \pm 2r \Rightarrow r = 2R \text{ or } -6R$$

The neutral point  $r = -6R$  does not concern us, so  $ON = 2R$ . It is enough to project the particle with a speed that lets it reach  $N$ ; after that, the greater pull of  $4M$  takes over.

Mechanical energy at the surface of  $M$ :

$$E_i = \frac{1}{2}mv^2 - \frac{GMm}{R} - \frac{4GMm}{5R}$$

At  $N$  the speed approaches zero, so the energy is purely potential:

$$E_N = -\frac{GMm}{2R} - \frac{4GMm}{4R}$$

By conservation of mechanical energy:

$$\frac{1}{2}v^2 - \frac{GM}{R} - \frac{4GM}{5R} = -\frac{GM}{2R} - \frac{GM}{R} \Rightarrow v^2 = \frac{2GM}{R} \left( \frac{4}{5} - \frac{1}{2} \right)$$

$$v = \left( \frac{3GM}{5R} \right)^{1/2}$$

The speed is zero at  $N$  but non-zero when the projectile strikes the heavier sphere.

### Example 7.5

**Question:** The planet Mars has two moons, Phobos and Deimos. (i) Phobos has a period 7 hours, 39 minutes and an orbital radius of  $9.4 \times 10^3$  km. Calculate the mass of Mars. (ii) Assume that earth and Mars move in circular orbits around the sun, with the Martian orbit being 1.52 times the orbital radius of the earth. What is the length of the Martian year in days?

**Solution:**

(i) Using Kepler's third law with the sun's mass replaced by the Martian mass  $M_m$ :

$$T^2 = \frac{4\pi^2}{GM_m} R^3 \Rightarrow M_m = \frac{4\pi^2 R^3}{GT^2}$$

$$M_m = \frac{4 \times (3.14)^2 \times (9.4 \times 10^3)^3 \times 10^{18}}{6.67 \times 10^{-11} \times (459 \times 60)^2} = 6.48 \times 10^{23} \text{ kg}$$

(ii) Kepler's third law:

$$\frac{T_M^2}{T_E^2} = \frac{R_{MS}^3}{R_{ES}^3} \Rightarrow T_M = (1.52)^{3/2} \times 365 = 684 \text{ days}$$

The orbits of all planets except Mercury and Mars are very close to circular (for the earth,  $b/a = 0.99986$ ).

**Answer:** (i)  $6.48 \times 10^{23}$  kg (ii) 684 days

### Example 7.6

**Question: Weighing the Earth:** You are given the following data:  $g = 9.81 \text{ m s}^{-2}$ ,  $R_E = 6.37 \times 10^6 \text{ m}$ , the distance to the moon  $R = 3.84 \times 10^8 \text{ m}$  and the time period of the moon's revolution is 27.3 days. Obtain the mass of the Earth  $M_E$  in two different ways.

**Solution:**

**Method 1** (from  $g$ ):

$$M_E = \frac{gR_E^2}{G} = \frac{9.81 \times (6.37 \times 10^6)^2}{6.67 \times 10^{-11}} = 5.97 \times 10^{24} \text{ kg}$$

**Method 2** (the moon as a satellite):

$$T^2 = \frac{4\pi^2 R^3}{GM_E} \Rightarrow M_E = \frac{4\pi^2 R^3}{GT^2} = \frac{4 \times 3.14 \times 3.14 \times (3.84 \times 10^8)^3 \times 10^{24}}{6.67 \times 10^{-11} \times (27.3 \times 24 \times 60 \times 60)^2} = 6.02 \times 10^{24} \text{ kg}$$

Both methods give almost the same answer; the difference is less than 1%.

### Example 7.7

**Question:** Express the constant  $k$  of Eq. (7.38) in days and kilometres. Given  $k = 10^{-13} \text{ s}^2 \text{ m}^{-3}$ . The moon is at a distance of  $3.84 \times 10^5 \text{ km}$  from the earth. Obtain its time-period of revolution in days.

**Solution:**

$$k = 10^{-13} \left[ \frac{1}{(24 \times 60 \times 60)^2} \text{ d}^2 \right] \left[ \frac{1}{(1/1000)^3} \text{ km}^3 \right] = 1.33 \times 10^{-14} \text{ d}^2 \text{ km}^{-3}$$

$$T^2 = (1.33 \times 10^{-14}) (3.84 \times 10^5)^3 \Rightarrow T = 27.3 \text{ d}$$

Eq. (7.38) also holds for elliptical orbits if  $(R_E + h)$  is replaced by the semi-major axis of the ellipse.

### Example 7.8

**Question:** A 400 kg satellite is in a circular orbit of radius  $2R_E$  about the Earth. How much energy is required to transfer it to a circular orbit of radius  $4R_E$ ? What are the changes in the kinetic and potential energies?

**Solution:**

$$E_i = -\frac{GM_E m}{4R_E}, \quad E_f = -\frac{GM_E m}{8R_E}$$

$$\Delta E = E_f - E_i = \frac{GM_E m}{8R_E} = \left( \frac{GM_E}{R_E^2} \right) \frac{mR_E}{8} = \frac{gmR_E}{8}$$

$$\Delta E = \frac{9.81 \times 400 \times 6.37 \times 10^6}{8} = 3.13 \times 10^9 \text{ J}$$

The kinetic energy is reduced and mimics  $\Delta E$ :  $\Delta K = K_f - K_i = -3.13 \times 10^9 \text{ J}$ .

The change in potential energy is twice the change in total energy:  $\Delta V = V_f - V_i = 6.25 \times 10^9 \text{ J}$ .

## Part B — NCERT Exercises

### Exercise 7.1

**Question:** Answer the following: (a) You can shield a charge from electrical forces by putting it inside a hollow conductor. Can you shield a body from the gravitational influence of nearby matter by putting it inside a hollow sphere or by some other means? (b) An astronaut inside a small space ship orbiting around the earth cannot detect gravity. If the space station orbiting around the earth has a large size, can he hope to detect gravity? (c) If you compare the gravitational force on the earth due to the sun to that due to the moon, you would find that the Sun's pull is greater than the moon's pull. However, the tidal effect of the moon's pull is greater than the tidal effect of the sun. Why?

**Answer:**

- **(a) No.** Gravitational force does not depend on the medium; gravitational shielding is not possible. A hollow sphere shields only from its own gravity, not from the gravity of matter outside it.
- **(b) Yes.** If the station is large enough, the variation of  $g$  across it (the tidal effect) becomes noticeable, and the astronaut can detect gravity.
- **(c)** The tidal effect depends on the **variation** of the force across the earth's diameter, which varies inversely as the **cube** of the distance. The moon is much closer than the sun, so its tidal effect is greater, although its pull is smaller.

### Exercise 7.2

**Question:** Choose the correct alternative: (a) Acceleration due to gravity increases/decreases with increasing altitude. (b) Acceleration due to gravity increases/decreases with increasing depth (assume the earth to be a sphere of uniform density). (c) Acceleration due to gravity is independent of mass of the earth/mass of the body. (d) The formula  $-GMm(1/r_2 - 1/r_1)$  is more/less accurate than the formula  $mg(r_2 - r_1)$  for the difference of potential energy between two points  $r_2$  and  $r_1$  distance away from the centre of the earth.

**Answer:** (a) **decreases** (b) **decreases** (c) **mass of the body** (d) **more** accurate

### Exercise 7.3

**Question:** Suppose there existed a planet that went around the Sun twice as fast as the earth. What would be its orbital size as compared to that of the earth?

**Solution:** "Twice as fast" means half the period:  $T_p = T_e/2$ . By Kepler's third law:

$$\frac{r_p}{r_e} = \left(\frac{T_p}{T_e}\right)^{2/3} = \left(\frac{1}{2}\right)^{2/3} = 0.63$$

**Answer:** The orbit is **0.63 times** the size of the earth's orbit.

### Exercise 7.4

**Question:** Io, one of the satellites of Jupiter, has an orbital period of 1.769 days and the radius of the orbit is  $4.22 \times 10^8$  m. Show that the mass of Jupiter is about one-thousandth that of the sun.

**Solution:**  $T = 1.769 \times 86400 = 1.528 \times 10^5$  s.

$$M_J = \frac{4\pi^2 r^3}{GT^2} = \frac{4\pi^2 \times (4.22 \times 10^8)^3}{6.67 \times 10^{-11} \times (1.528 \times 10^5)^2} = 1.9 \times 10^{27} \text{ kg}$$

With  $M_S = 2 \times 10^{30}$  kg:

$$\frac{M_J}{M_S} = \frac{1.9 \times 10^{27}}{2 \times 10^{30}} \approx \frac{1}{1000}$$

(Equivalently, comparing with the earth's orbit about the sun gives the same ratio.)

### Exercise 7.5

**Question:** Let us assume that our galaxy consists of  $2.5 \times 10^{11}$  stars each of one solar mass. How long will a star at a distance of 50,000 ly from the galactic centre take to complete one revolution? Take the diameter of the Milky Way to be  $10^5$  ly.

**Solution:**  $M = 2.5 \times 10^{11} \times 2 \times 10^{30} = 5 \times 10^{41}$  kg;  $r = 5 \times 10^4 \times 9.46 \times 10^{15} = 4.73 \times 10^{20}$  m.

$$T = 2\pi\sqrt{\frac{r^3}{GM}} = 2\pi\sqrt{\frac{(4.73 \times 10^{20})^3}{6.67 \times 10^{-11} \times 5 \times 10^{41}}} = 1.12 \times 10^{16} \text{ s}$$

$$T = \frac{1.12 \times 10^{16}}{3.15 \times 10^7} \approx 3.5 \times 10^8 \text{ years}$$

**Answer:** About  $3.5 \times 10^8$  years.

### Exercise 7.6

**Question:** Choose the correct alternative: (a) If the zero of potential energy is at infinity, the total energy of an orbiting satellite is negative of its kinetic/potential energy. (b) The energy required to launch an orbiting satellite out of earth's gravitational influence is more/less than the energy required to project a stationary object at the same height (as the satellite) out of earth's influence.

**Answer:** (a) **kinetic** energy ( $E = -K$ ) (b) **less** — the orbiting satellite already has kinetic energy.

### Exercise 7.7

**Question:** Does the escape speed of a body from the earth depend on (a) the mass of the body, (b) the location from where it is projected, (c) the direction of projection, (d) the height of the location from where the body is launched?

**Answer:**

- (a) **No** —  $v_e = \sqrt{2GM/R}$  is independent of the body's mass.
- (b) **Yes**, slightly —  $g$  (and the effect of the earth's rotation) varies with latitude.
- (c) **No** — escape depends on energy, which is a scalar (ignoring the earth's rotation).
- (d) **Yes** —  $v_e = \sqrt{2GM/(R+h)}$  decreases with height.

### Exercise 7.8

**Question:** A comet orbits the sun in a highly elliptical orbit. Does the comet have a constant (a) linear speed, (b) angular speed, (c) angular momentum, (d) kinetic energy, (e) potential energy, (f) total energy throughout its orbit? Neglect any mass loss of the comet when it comes very close to the Sun.

**Answer:** Only (c) **angular momentum** and (f) **total energy** are constant. Linear speed, angular speed, kinetic energy and potential energy all vary along the orbit.

### Exercise 7.9

**Question:** Which of the following symptoms is likely to afflict an astronaut in space (a) swollen feet, (b) swollen face, (c) headache, (d) orientational problem?

**Answer: (b) Swollen face** — in weightlessness, body fluids are not pulled down to the feet and accumulate in the face. **(c) Headache** — due to the extra fluid in the head. **(d) Orientational problem** — there is no “up” or “down” in free fall. Swollen feet (a) do not occur.

### Exercise 7.10

**Question:** The gravitational intensity at the centre of a hemispherical shell of uniform mass density has the direction indicated by the arrow (see Fig 7.11) (i) a, (ii) b, (iii) c, (iv) 0.

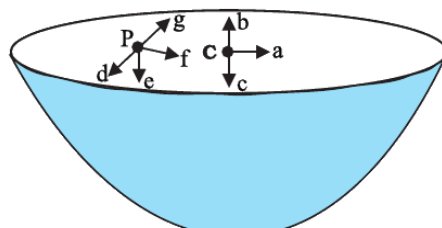


Fig. 7.11

**Solution:** For a complete spherical shell, the intensity inside is zero. Removing the upper hemisphere removes its (upward) contribution, so the lower hemisphere's field at the centre points **downward**.

**Answer: (iii) c**

### Exercise 7.11

**Question:** For the above problem, the direction of the gravitational intensity at an arbitrary point P is indicated by the arrow (i) d, (ii) e, (iii) f, (iv) g.

**Answer:** By the same argument, the field at any point P on the flat face is **vertically downward: (ii) e**.

### Exercise 7.12

**Question:** A rocket is fired from the earth towards the sun. At what distance from the earth's centre is the gravitational force on the rocket zero? Mass of the sun =  $2 \times 10^{30}$  kg, mass of the earth =  $6 \times 10^{24}$  kg. Neglect the effect of other planets etc. (orbital radius =  $1.5 \times 10^{11}$  m).

**Solution:** At distance  $x$  from the earth:

$$\frac{GM_E}{x^2} = \frac{GM_S}{(r-x)^2} \Rightarrow \frac{r-x}{x} = \sqrt{\frac{M_S}{M_E}} = \sqrt{\frac{2 \times 10^{30}}{6 \times 10^{24}}} = 577$$

$$x = \frac{r}{578} = \frac{1.5 \times 10^{11}}{578} = 2.6 \times 10^8 \text{ m}$$

**Answer:**  $2.6 \times 10^8$  m from the earth's centre

### Exercise 7.13

**Question:** How will you 'weigh the sun', that is estimate its mass? The mean orbital radius of the earth around the sun is  $1.5 \times 10^8$  km.

**Solution:** The sun's gravity provides the centripetal force on the earth:  $\frac{GM_S m}{r^2} = m \frac{4\pi^2}{T^2} r$ . With  $T = 365$  days =  $3.15 \times 10^7$  s and  $r = 1.5 \times 10^{11}$  m:

$$M_S = \frac{4\pi^2 r^3}{GT^2} = \frac{4\pi^2 \times (1.5 \times 10^{11})^3}{6.67 \times 10^{-11} \times (3.15 \times 10^7)^2} = 2.0 \times 10^{30} \text{ kg}$$

### Exercise 7.14

**Question:** A Saturn year is 29.5 times the earth year. How far is the Saturn from the sun if the earth is  $1.50 \times 10^8$  km away from the sun?

**Solution:**

$$r_S = r_E \left( \frac{T_S}{T_E} \right)^{2/3} = 1.5 \times 10^8 \times (29.5)^{2/3} = 1.43 \times 10^9 \text{ km}$$

**Answer:**  $1.43 \times 10^{12}$  m

### Exercise 7.15

**Question:** A body weighs 63 N on the surface of the earth. What is the gravitational force on it due to the earth at a height equal to half the radius of the earth?

**Solution:**

$$W_h = W \left( \frac{R}{R + R/2} \right)^2 = 63 \times \frac{4}{9} = 28 \text{ N}$$

**Answer:** 28 N

### Exercise 7.16

**Question:** Assuming the earth to be a sphere of uniform mass density, how much would a body weigh half way down to the centre of the earth if it weighed 250 N on the surface?

**Solution:**  $g_d = g \left( 1 - \frac{d}{R} \right) = g \left( 1 - \frac{1}{2} \right) = \frac{g}{2}$ . Weight =  $\frac{250}{2} = 125$  N.

**Answer:** 125 N

### Exercise 7.17

**Question:** A rocket is fired vertically with a speed of  $5 \text{ km s}^{-1}$  from the earth's surface. How far from the earth does the rocket go before returning to the earth? Mass of the earth =  $6.0 \times 10^{24}$  kg; mean radius of the earth =  $6.4 \times 10^6$  m;  $G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$ .

**Solution:** By energy conservation ( $r$  = distance from the centre at the highest point):

$$\frac{1}{2}mv^2 - \frac{GMm}{R} = -\frac{GMm}{r} \Rightarrow \frac{1}{r} = \frac{1}{R} - \frac{v^2}{2GM}$$

$$\frac{1}{r} = \frac{1}{6.4 \times 10^6} - \frac{(5 \times 10^3)^2}{2 \times 6.67 \times 10^{-11} \times 6 \times 10^{24}} \Rightarrow r = 8.0 \times 10^6 \text{ m}$$

Height above the surface:  $h = 8.0 \times 10^6 - 6.4 \times 10^6 = 1.6 \times 10^6$  m.

**Answer:**  $1.6 \times 10^6$  m (1600 km) above the surface

### Exercise 7.18

**Question:** The escape speed of a projectile on the earth's surface is  $11.2 \text{ km s}^{-1}$ . A body is projected out with thrice this speed. What is the speed of the body far away from the earth? Ignore the presence of the sun and other planets.

**Solution:** By energy conservation:  $\frac{1}{2}mv^2 - \frac{1}{2}mv_e^2 = \frac{1}{2}mv_\infty^2$  (since  $\frac{1}{2}mv_e^2 = GMm/R$ ).

$$v_\infty = \sqrt{v^2 - v_e^2} = \sqrt{(3v_e)^2 - v_e^2} = \sqrt{8} v_e = 2.83 \times 11.2 = 31.7 \text{ km s}^{-1}$$

**Answer:**  $\approx 31.7 \text{ km s}^{-1}$

### Exercise 7.19

**Question:** A satellite orbits the earth at a height of 400 km above the surface. How much energy must be expended to rocket the satellite out of the earth's gravitational influence? Mass of the satellite = 200 kg; mass of the earth =  $6.0 \times 10^{24} \text{ kg}$ ; radius of the earth =  $6.4 \times 10^6 \text{ m}$ ;  $G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$ .

**Solution:** Total energy in orbit:  $E = -\frac{GMm}{2(R+h)}$ . The energy needed to escape (to make  $E = 0$ ) is

$$\Delta E = \frac{GMm}{2(R+h)} = \frac{6.67 \times 10^{-11} \times 6 \times 10^{24} \times 200}{2 \times 6.8 \times 10^6} = 5.9 \times 10^9 \text{ J}$$

**Answer:**  $5.9 \times 10^9 \text{ J}$

### Exercise 7.20

**Question:** Two stars each of one solar mass ( $= 2 \times 10^{30} \text{ kg}$ ) are approaching each other for a head on collision. When they are at a distance  $10^9 \text{ km}$ , their speeds are negligible. What is the speed with which they collide? The radius of each star is  $10^4 \text{ km}$ . Assume the stars to remain undistorted until they collide. (Use the known value of  $G$ .)

**Solution:** Initial separation  $d_i = 10^{12} \text{ m}$ ; at collision the centres are  $d_f = 2 \times 10^7 \text{ m}$  apart. By energy conservation (each star has speed  $v$ ):

$$-\frac{GM^2}{d_i} = 2 \cdot \frac{1}{2} Mv^2 - \frac{GM^2}{d_f} \Rightarrow v^2 = GM \left( \frac{1}{d_f} - \frac{1}{d_i} \right)$$

$$v^2 = 6.67 \times 10^{-11} \times 2 \times 10^{30} \times \left( \frac{1}{2 \times 10^7} - \frac{1}{10^{12}} \right) \approx 6.67 \times 10^{12} \Rightarrow v = 2.6 \times 10^6 \text{ m/s}$$

**Answer:** Each star moves at about  $2.6 \times 10^6 \text{ m/s}$  at collision.

### Exercise 7.21

**Question:** Two heavy spheres each of mass 100 kg and radius 0.10 m are placed 1.0 m apart on a horizontal table. What is the gravitational force and potential at the mid point of the line joining the centres of the spheres? Is an object placed at that point in equilibrium? If so, is the equilibrium stable or unstable?

**Solution:**

- **Field (force):** The two spheres pull equally in opposite directions, so the net gravitational force at the midpoint is **zero**.
- **Potential:** Each sphere is 0.5 m away:

$$V = -2 \times \frac{GM}{r} = -2 \times \frac{6.67 \times 10^{-11} \times 100}{0.5} = -2.7 \times 10^{-8} \text{ J/kg}$$

- An object placed there is **in equilibrium** (zero net force). The equilibrium is **unstable**: if displaced slightly towards either sphere, the pull of the nearer sphere becomes stronger and the object moves further away from the midpoint.