Institut Teknologi Sepuluh Nopember
Surabaya

HUKUM NEWTON GRAVITASI

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Tutug Dhanardono

- Pengantar
- Materi
- Contoh Soal
- Ringkasan
- Latihan
- Asesmen

Pengantar

Materi

Contoh Soal

Ringkasan

Latihan

Asesmen

Hukum Newton Gravitasi

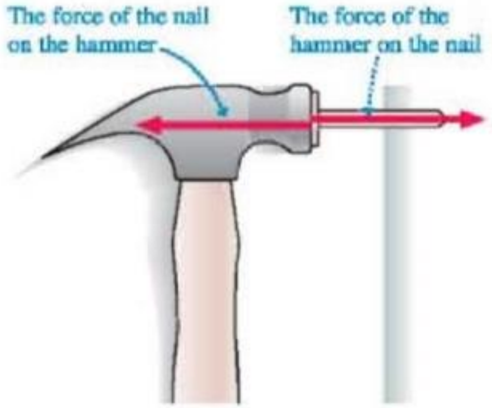
Hukum Kepler

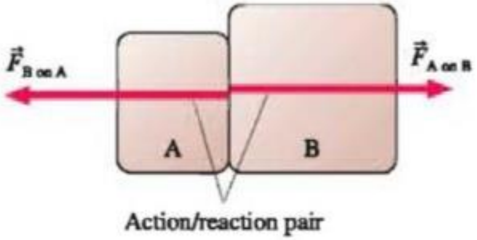
Pengantar

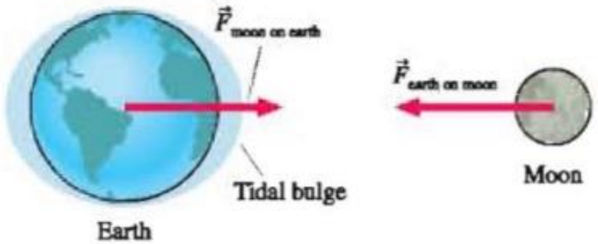
Capaian Pembelajaran

1. Mampu menjelaskan tentang konsep Hukum Newton gravitasi
2. Mampu menjelaskan tentang konsep gerakan bulan
3. Mampu menjelaskan tentang Hukum Kepler

Pengantar

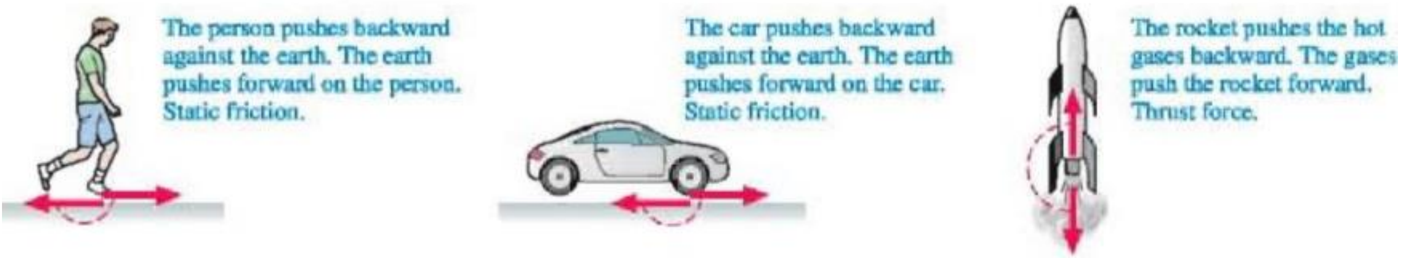






Gaya Aksi ~ Reaksi
Pada sebuah materi
Pada sebuah sistem

Materi



Newton's third law Every force occurs as one member of an action/reaction pair of forces.

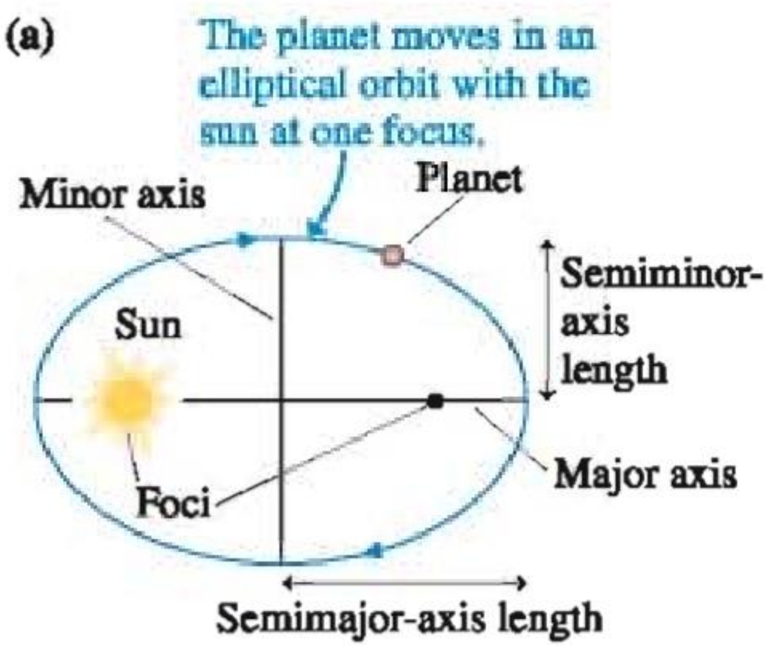
- The two members of an action/reaction pair act on two *different* objects.
- The two members of an action/reaction pair are equal in magnitude but opposite in direction: $\vec{F}_{\text{A on B}} = -\vec{F}_{\text{B on A}}$.

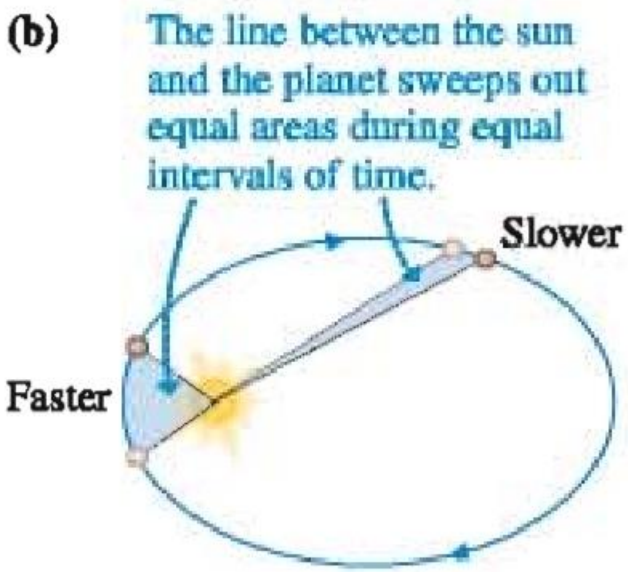
Hukum Newton III

Materi

Apakah pada sistem tata surya juga berlaku Hukum Newton III

Gerakan (perputaran) planit mengelilingi Matahari, merupakan sebuah orbit berbentuk elipse

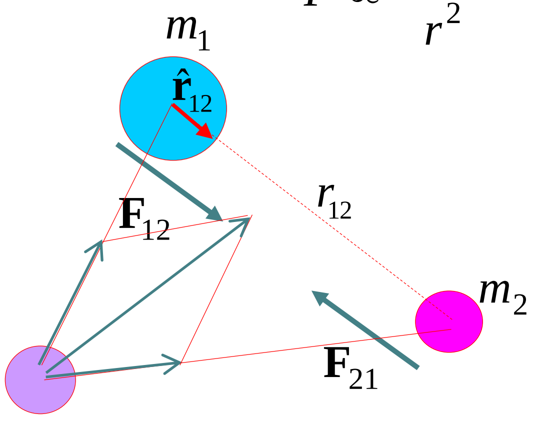




Hukum Newton tentang Gravitasi Semesta

Setiap partikel di alam menarik partikel lain dengan gaya yang besarnya berbanding langsung dengan hasil kali masa kedua partikel tersebut dan berbanding terbalik dengan kwadrat jarak antara kedua massa tersebut.

Ingatkah ttg Vektor satuan?



$$F \propto \frac{m_1 m_2}{r^2} \longrightarrow F = G\frac{m_1 m_2}{r^2}$$

konstanta gravitasi

$$G = 6.672 \times 10^{-11} \frac{N \cdot m^2}{kg^2}$$

$$\mathbf{F}_{12} = -G\frac{m_1 m_2}{r_{12}^2}\hat{\mathbf{r}}_{12}$$

$$\mathbf{F}_{21} = -\mathbf{F}_{12}$$

$$\mathbf{F}_3 = \mathbf{F}_{31} + \mathbf{F}_{32}$$

$$F_3 = \sqrt{F_{31}^2 + F_{32}^2 + 2F_{31}F_{32}\cos\theta}$$

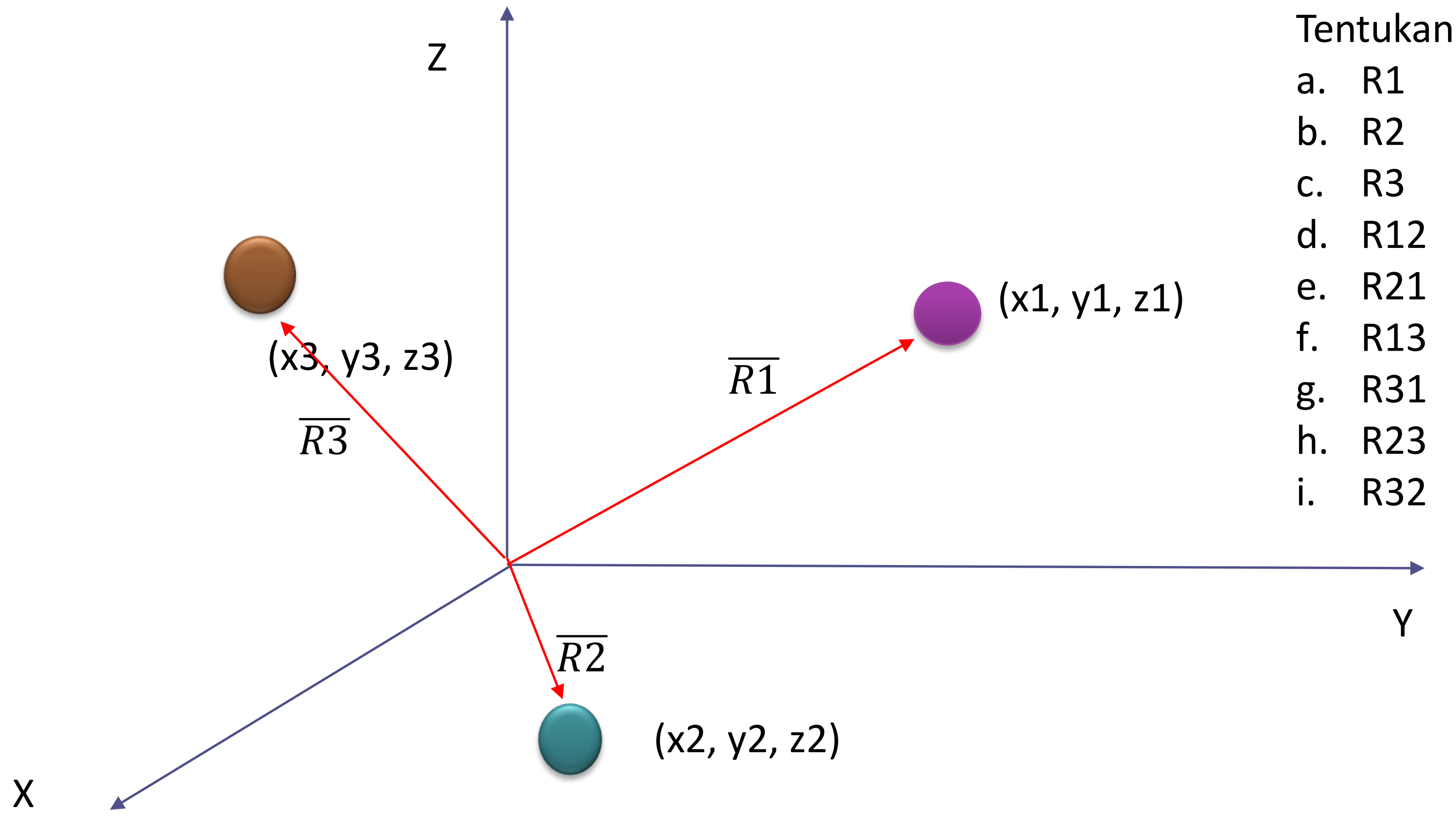
Bagaimana gaya gravitasi oleh massa berbentuk bola ?

Gaya gravitasi pada massa m di permukaan bumi : $F = G\frac{M_B m}{R_B^2}$

massa bumi

Jari-jari bumi

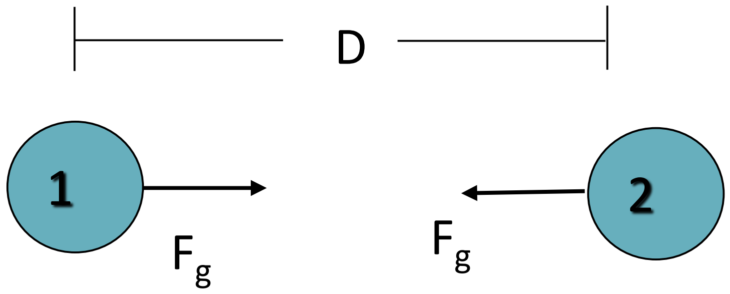
Materi



Tentukan Vektor:

a. R1
b. R2
c. R3
d. R12
e. R21
f. R13
g. R31
h. R23
i. R32

Materi



$$F_g = \frac{GM_1M_2}{D^2}$$

M_1 = Mass of object 1 (kg)

M_2 = Mass of object 2 (kg)

D = Distance between objects (m)

G = 6.67×10^{-11} $m^3/sec^2/kg$

$$F = G\frac{M_B m}{R_B^2}$$

Berat benda pada permukaan bumi ← $W = mg$

$$\longrightarrow g = G\frac{M_B}{R_B^2} \approx 9.80\, m/s^2$$

G: $6.672 \times 10^{-11}\ \dfrac{N \cdot m^2}{kg^2}$

M_B: $\approx 5.98 \times 10^{24}\,\mathrm{kg}$

R_B: $\approx 6.38 \times 10^{6}\,\mathrm{m}$

Bagaimana berat benda pada ketinggian h dari permukaan bumi ?

$$F = G\frac{M_B m}{r^2}$$

Jarak benda ke pusat bumi ← $r = R_B + h$

$$\longrightarrow F = G\frac{M_B m}{(R_B + h)^2}$$

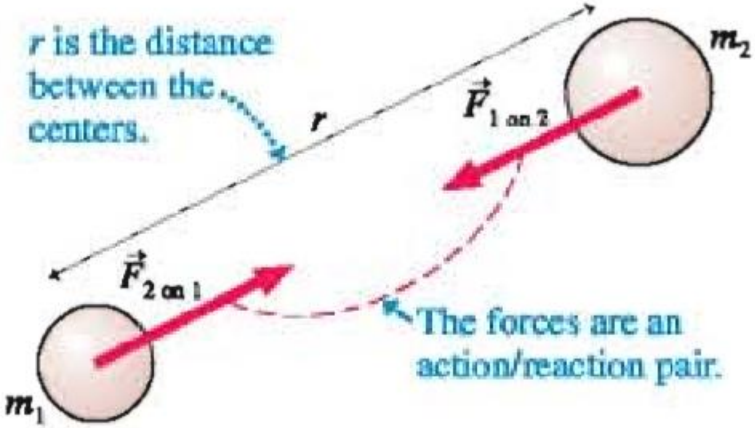
$$W' = mg'$$

$$\longrightarrow g' = G\frac{M_B}{(R_B + h)^2}$$

Semakin jauh dari permukaan bumi, percepatan gravitasi semakin kecil

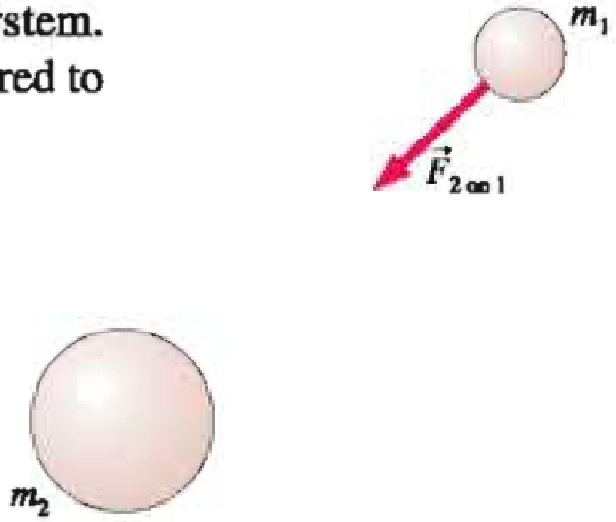
Materi

Soal no 1, kerjakan dalam waktu 5 menit, potret dan upload di FB



STOP TO THINK 13.2 The figure shows a binary star system. The mass of star 2 is twice the mass of star 1. Compared to $\vec{F}_{1 \text{ on } 2}$, the magnitude of the force $\vec{F}_{2 \text{ on } 1}$ is

a. Four times as big.
b. Twice as big.
c. The same size.
d. Half as big.
e. One-quarter as big.



Materi

Bagaimana berat benda pada ketinggian h dari permukaan bumi ?

Jarak benda ke pusat bumi

$$F = G\frac{M_B m}{r^2}$$

$$r = R_B + h$$

$$\longrightarrow F = G\frac{M_B m}{(R_B + h)^2}$$

$$W' = mg'$$

$$\longrightarrow g' = G\frac{M_B}{(R_B + h)^2}$$

M_B: 5,98x10^{24} kg

R_B: 6,37x10^{6} m

$$g = \frac{GM_e}{(R_e + h)^2} = \frac{GM_e}{R_e^2(1 + h/R_e)^2} = \frac{g_{earth}}{(1 + h/R_e)^2} \tag{13.9}$$

where $g_{earth} = 9.83$ m/s^2 is the value calculated from Equation 13.7 for $h = 0$ on a nonrotating earth. Table 13.1 shows the value of g evaluated at several values of h.

TABLE 13.1 Variation of g with height above the ground

Height h	Example	g (m/s^2)
0 m	ground	9.83
4500 m	Mt. Whitney	9.82
10,000 m	jet airplane	9.80
300,000 m	space shuttle	8.90
35,900,000 m	communications satellite	0.22

Materi

Soal no 2, kerjakan dalam waktu 5 menit, potret dan upload di FB

STOP TO THINK 13.3 A planet has four times the mass of the earth, but the acceleration due to gravity on the planet's surface is the same as on the earth's surface. The planet's radius is

a. $4R_e$ b. $2R_e$ c. R_e d. $\frac{1}{2}R_e$ e. $\frac{1}{4}R_e$

Materi

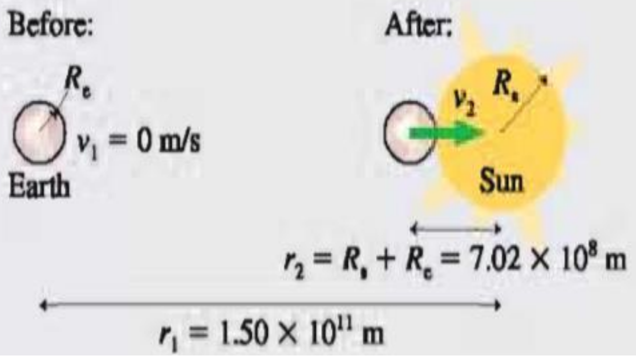
EXAMPLE 13.1 Crashing into the sun

Suppose the earth were suddenly to cease revolving around the sun. The gravitational force would then pull it directly into the sun. What would be the earth's speed as it crashed?

MODEL Model the earth and the sun as spherical masses. This is an isolated system, so its mechanical energy is conserved.

VISUALIZE FIGURE 13.13 is a before-and-after pictorial representation for this gruesome cosmic event. The "crash" occurs as the earth touches the sun, at which point the distance between their centers is $r_2 = R_s + R_e$. The initial separation r_1 is the radius of the earth's *orbit* about the sun, not the radius of the earth.

FIGURE 13.13 Before-and-after pictorial representation of the earth crashing into the sun (not to scale).



SOLVE Strictly speaking, the kinetic energy is the sum $K = K_{earth} + K_{sun}$. However, the sun is so much more massive than the earth that the lightweight earth does almost all of the moving. It is a reasonable approximation to consider the sun as remaining at rest. In that case, the energy conservation equation $K_2 + U_2 = K_1 + U_1$ is

$$\frac{1}{2}M_e v_2^2 - \frac{GM_sM_e}{R_s + R_e} = 0 - \frac{GM_sM_e}{r_1}$$

This is easily solved for the earth's speed at impact. Using data from Table 13.2, we find

$$v_2 = \sqrt{2GM_s\left(\frac{1}{R_s + R_e} - \frac{1}{r_1}\right)} = 6.13 \times 10^5 \text{ m/s}$$

ASSESS The earth would be really flying along at over 1 million miles per hour as it crashed into the sun! It is worth noting that we do not have the mathematical tools to solve this problem using Newton's second law because the acceleration is not constant. But the solution is straightforward when we use energy conservation.

Hukum Kepler

- ***Betulkah bumi mengelilingi matahari ?***
- ***Mengapa planet-planet mengelilingi matahari ?***
- ***Bagaimana lintasan orbit planet-planet tersebut ?***

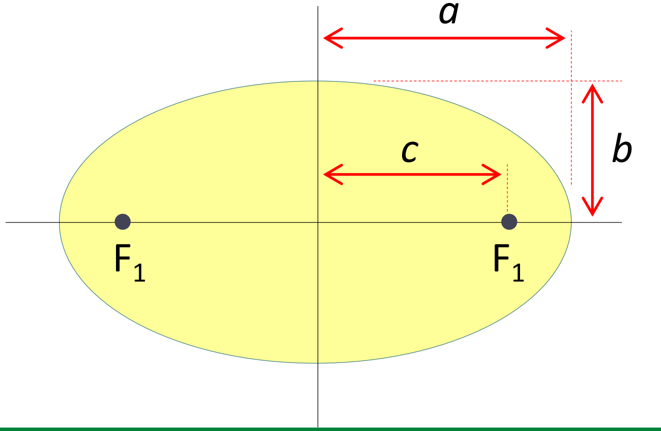
1. Semua planet beredar dalam lintasan elip dengan matahari sebagai fokus.
2. Vektor posisi setiap planet terhadap matahari dalam interval waktu yang sama menyapu luasan yang sama pula.
3. Kwadrat perioda orbit setiap planet sebanding dengan pangkat tiga dari sumbu mayor lintasannya.

Apakah Hukum Newton tentang Gravitasi sesuai dengan pernyataan ini ?

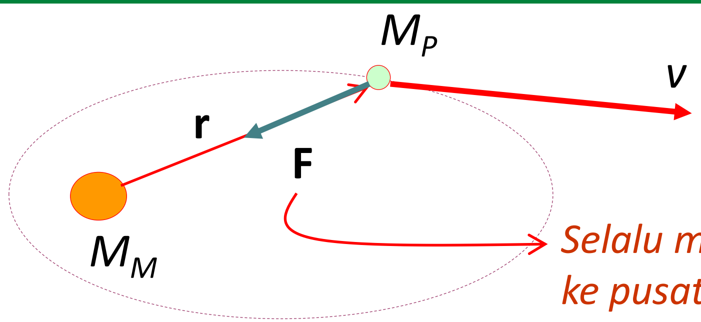
Misal orbit planet terhadap matahari adalah lingkaran :

$$G\frac{M_M M_P}{r^2} = \frac{M_P v^2}{r} \qquad v = 2\pi r/T$$

$$G\frac{M_M}{r} = (2\pi r/T)^2 \longrightarrow T^2 = \underbrace{\left(\frac{4\pi^2}{GM_M}\right)}_{K_M} r^3$$



Hukum Kepler II dan Kekekalan Momentum Sudut



Selalu menuju ke pusat orbit

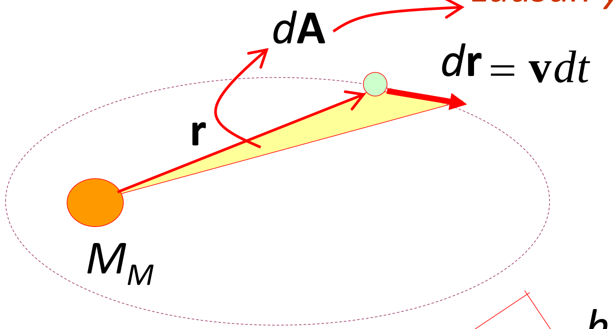
Momen gaya :

$$\boldsymbol{\tau} = \mathbf{r}\times\mathbf{F} = \mathbf{r}\times F(r)\hat{\mathbf{r}} = 0$$

$$\boldsymbol{\tau} = \frac{d\mathbf{L}}{dt} = 0 \longrightarrow \mathbf{L} = \text{konstan}$$

$$\mathbf{L} = \mathbf{r}\times\mathbf{p} = m(\mathbf{r}\times\mathbf{v}) \quad ?$$

*Luasan yang disapu **r** dalam selang waktu dt*

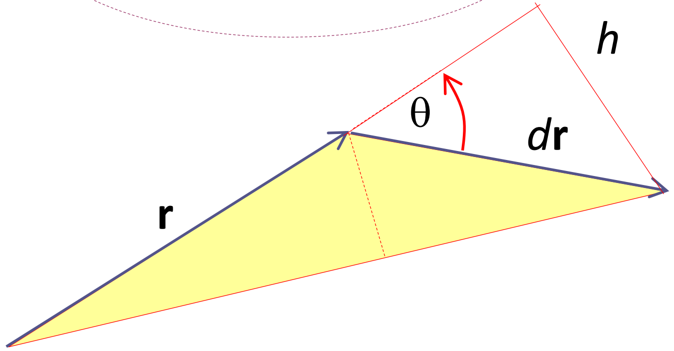


$$\left.\begin{aligned} dA &= \tfrac{1}{2}rh \\ h &= dr\sin\theta \end{aligned}\right\} \longrightarrow dA = \tfrac{1}{2}r\,dr\sin\theta = \tfrac{1}{2}|\mathbf{r}\times d\mathbf{r}|$$

$$= \tfrac{1}{2}|\mathbf{r}\times\mathbf{v}dt|$$

$$|\mathbf{r}\times\mathbf{v}| = 2\frac{dA}{dt} = \frac{L}{m}$$

$$\frac{dA}{dt} = \frac{L}{2m} = \text{konstan}$$



Dalam interval waktu yang sama posisi **r** menyapu luasan yang sama pula

Medan Gravitasi dan Potensial Gravitasi

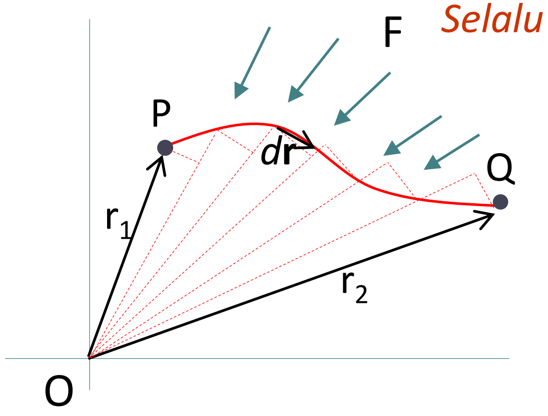
Medan Gravitasi : $\mathbf{g} \equiv \dfrac{\mathbf{F}}{m}$

Gaya yang dialami oleh massa uji m di dalam medan gravitasi g

Medan Gravitasi bumi : $\mathbf{g}_B = \dfrac{\mathbf{F}}{m} = -\dfrac{GM_B}{r^2}\hat{\mathbf{r}}$

Selalu menuju ke O

Gaya terpusat $\longrightarrow$ $\mathbf{F} = F(r)\hat{\mathbf{r}}$



$$dW = \mathbf{F}\cdot d\mathbf{r} = F(r)dr$$

$$W = \int_{r_1}^{r_2} F(r)dr$$

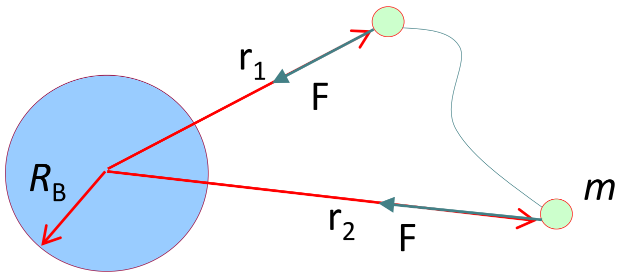
Usaha hanya tergantung pada posisi awal dan akhir

$$\Delta U = U_f - U_i = -\int_{r_1}^{r_2} F(r)dr$$

$$\mathbf{F} = -\frac{GM_B m}{r^2}\hat{\mathbf{r}}$$

$$U_f - U_i = GM_B m \int_{r_1}^{r_2} \frac{dr}{r^2} = GM_B m \left[-\frac{1}{r}\right]_{r_1}^{r_2}$$

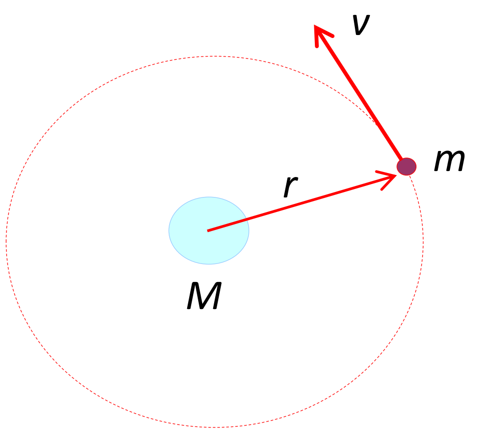
$$U_f - U_i = GM_B m \left[\frac{1}{r_f} - \frac{1}{r_i}\right] \quad r_i \to \infty$$



$$U(r) = \frac{GM_B m}{r}$$

Energi potensial massa m pada posisi r

Energi Gerak Planet dan Satelit



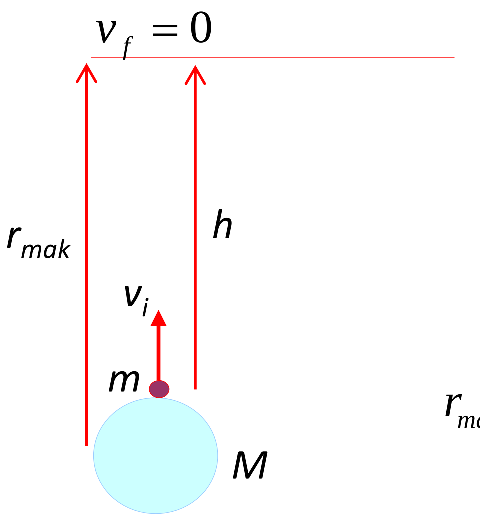
$$E = \tfrac{1}{2} mv^2 - G\frac{Mm}{r}$$

Hukum Newton II : $\dfrac{GMm}{r^2} = \dfrac{mv^2}{r}$

$$\tfrac{1}{2} mv^2 = \frac{GMm}{2r}$$

$$E = G\frac{Mm}{2r} - G\frac{Mm}{r} = -\frac{GMm}{2r}$$

Berapakah kecepatan minimum benda untuk lepas dari gravitasi bumi ?



$$\tfrac{1}{2} mv_i^2 - G\frac{M_B m}{R_B} = -G\frac{M_B m}{r_{mak}} \qquad h = r_{mak} - R_B$$

$$v_i^2 = 2GM_B\left(\frac{1}{R_B} - \frac{1}{r_{mak}}\right)$$

$$r_{mak} \to \infty \longrightarrow v_{esc} = \sqrt{\frac{2GM_B}{R_B}}$$

Materi

Materi

EXAMPLE 13.3 The speed of a satellite

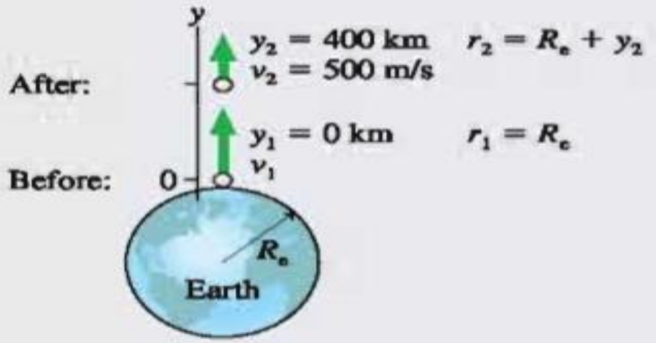
A less-than-successful inventor wants to launch small satellites into orbit by launching them straight up from the surface of the earth at very high speed.

a. With what speed should he launch the satellite if it is to have a speed of 500 m/s at a height of 400 km? Ignore air resistance.
b. By what percentage would your answer be in error if you used a flat-earth approximation?

MODEL Mechanical energy is conserved if we ignore drag.

VISUALIZE FIGURE 13.16 shows a pictorial representation.

FIGURE 13.16 Pictorial representation of a satellite launched straight up.



SOLVE a. Although the height is exaggerated in the figure, 400 km = 400,000 m is high enough that we cannot ignore the earth's spherical shape. The energy conservation equation $K_2 + U_2 = K_1 + U_1$ is

$$\frac{1}{2}mv_2^2 - \frac{GM_em}{R_e + y_2} = \frac{1}{2}mv_1^2 - \frac{GM_em}{R_e + y_1}$$

where we've written the distance between the satellite and the earth's center as $r = R_e + y$. The initial height is $y_1 = 0$. Notice that the satellite mass m cancels and is not needed. Solving for the launch speed, we have

$$v_1 = \sqrt{v_2^2 + 2GM_e\left(\frac{1}{R_e} - \frac{1}{R_e + y_2}\right)} = 2770 \text{ m/s}$$

This is about 6000 mph, much less than the escape speed.

b. The calculation is the same in the flat-earth approximation except that we use $U_g = mgy$. Thus

$$\frac{1}{2}mv_2^2 + mgy_2 = \frac{1}{2}mv_1^2 + mgy_1$$

$$v_1 = \sqrt{v_2^2 + 2gy_2} = 2840 \text{ m/s}$$

The flat-earth value of 2840 m/s is 70 m/s too big. The error, as a percentage of the correct 2770 m/s, is

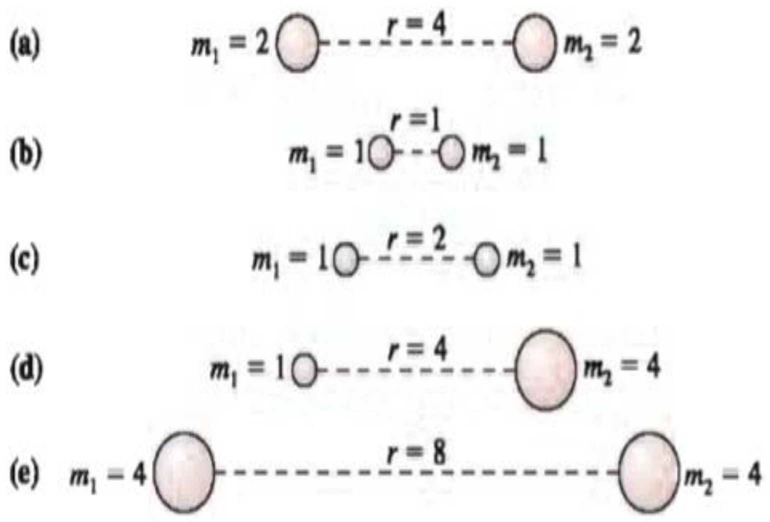
$$\text{error} = \frac{70}{2770} \times 100 = 2.5\%$$

ASSESS The true speed is less than the flat-earth approximation because the force of gravity decreases with height. Launching a rocket against a decreasing force takes less effort than it would with the flat-earth force of mg at all heights.

Materi

Soal no 3, kerjakan dalam waktu 10 menit, potret dan upload di FB

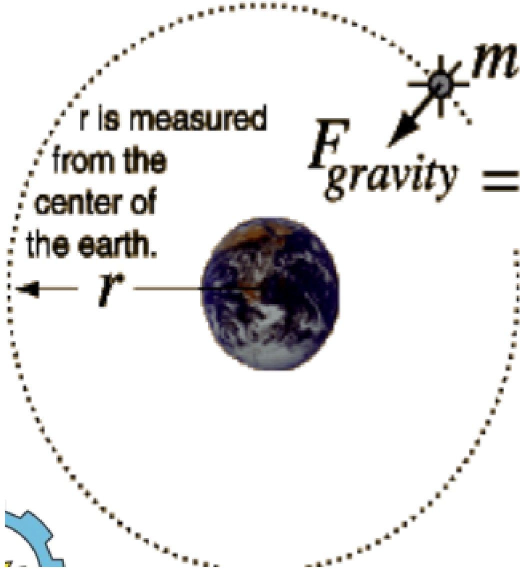
STOP TO THINK 13.4 Rank in order, from largest to smallest, the absolute values of the gravitational potential energies of these pairs of masses. The numbers give the relative masses and distances.



Materi

Orbit edar

Agar satelit tetap berada pada orbit edarnya (dalam mengitari bumi), dengan radius yang tetap, maka **Gaya Gravitasi** harus **sama dengan Gaya Sentripetal**



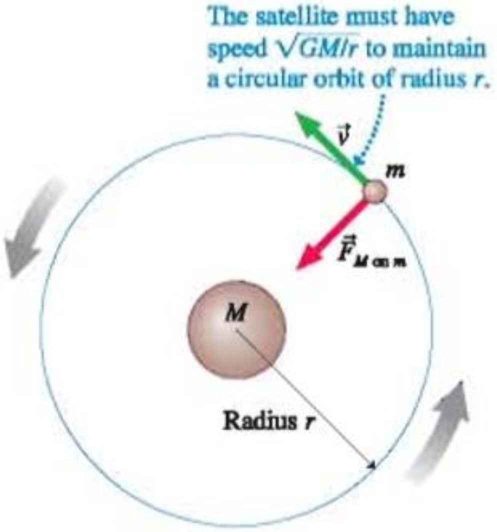
$$F_{gravity} = mg_{orbit} = m\frac{v^2}{r} = F_{centripetal}$$

$$v_{orbit} = \sqrt{rg_{orbit}}$$

$$g_{orbit} = g_{surface}\left[\frac{R_{Earth}}{r}\right]^2$$

Materi

FIGURE 13.17 The orbital motion of a satellite due to the force of gravity.



The International Space Station appears to be floating, but it's actually traveling at nearly 8000 m/s as it orbits the earth.

FIGURE 13.17 shows a massive body M, such as the earth or the sun, with a lighter body m orbiting it. The lighter body is called a **satellite,** even though it may be a planet orbiting the sun. Newton's second law for the satellite is

$$F_{M \text{ on } m} = \frac{GMm}{r^2} = ma_r = \frac{mv^2}{r} \tag{13.21}$$

Thus the speed of a satellite in a circular orbit is

$$\boxed{v = \sqrt{\frac{GM}{r}}} \tag{13.22}$$

A satellite must have this specific speed in order to have a circular orbit of radius r about the larger mass M. If the velocity differs from this value, the orbit will become elliptical rather than circular. Notice that the orbital speed does *not* depend on the satellite's mass m. This is consistent with our previous discovery, for motion on a flat earth, that motion due to gravity is independent of the mass.

Materi

Kepler's Third Law

An important parameter of circular motion is the *period*. Recall that the period T is the time to complete one full orbit. The relationship among speed, radius, and period is

$$v = \frac{\text{circumference}}{\text{period}} = \frac{2\pi r}{T} \tag{13.23}$$

We can find a relationship between a satellite's period and the radius of its orbit by using Equation 13.22 for v:

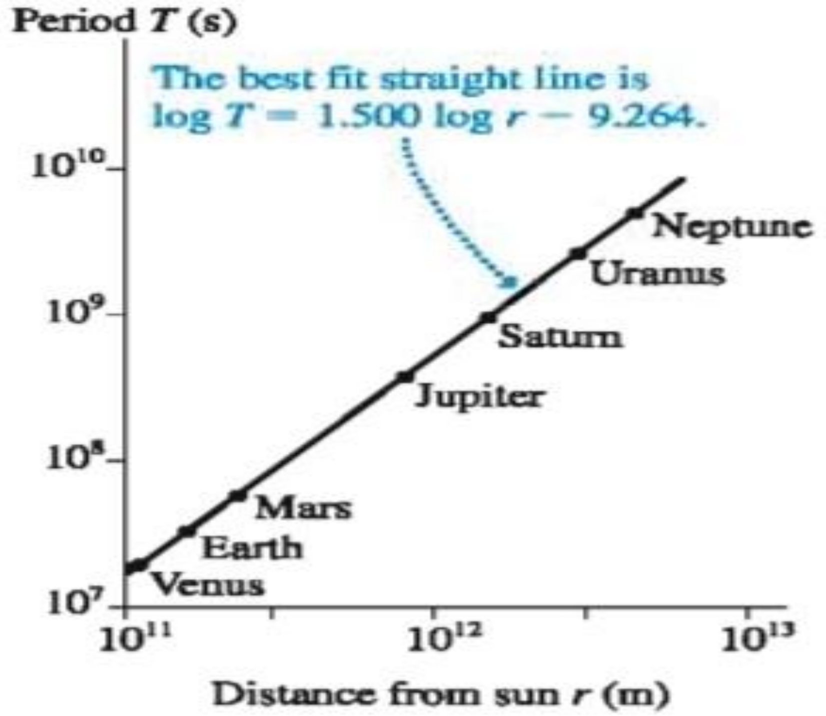
$$v = \frac{2\pi r}{T} = \sqrt{\frac{GM}{r}} \tag{13.24}$$

Squaring both sides and solving for T give

$$T^2 = \left(\frac{4\pi^2}{GM}\right) r^3 \tag{13.25}$$

In other words, the *square* of the period is proportional to the *cube* of the radius. This is Kepler's third law. You can see that Kepler's third law is a direct consequence of Newton's law of gravity.

FIGURE 13.18 The graph of $\log T$ versus $\log r$ for the planetary data of Table 13.2.



Materi

TABLE 13.2 Useful astronomical data

Planetary body	Mean distance from sun (m)	Period (years)	Mass (kg)	Mean radius (m)
Sun	–	–	1.99×10^{30}	6.96×10^{8}
Moon	3.84×10^{8}*	27.3 days	7.36×10^{22}	1.74×10^{6}
Mercury	5.79×10^{10}	0.241	3.18×10^{23}	2.43×10^{6}
Venus	1.08×10^{11}	0.615	4.88×10^{24}	6.06×10^{6}
Earth	1.50×10^{11}	1.00	5.98×10^{24}	6.37×10^{6}
Mars	2.28×10^{11}	1.88	6.42×10^{23}	3.37×10^{6}
Jupiter	7.78×10^{11}	11.9	1.90×10^{27}	6.99×10^{7}
Saturn	1.43×10^{12}	29.5	5.68×10^{26}	5.85×10^{7}
Uranus	2.87×10^{12}	84.0	8.68×10^{25}	2.33×10^{7}
Neptune	4.50×10^{12}	165	1.03×10^{26}	2.21×10^{7}

*Distance from earth.

Soal Latihan

1

20. Three satellites orbit a planet of radius R, as shown in FIGURE EX13.20. Satellites S_1 and S_3 have mass m. Satellite S_2 has mass $2m$. Satellite S_1 orbits in 250 minutes and the force on S_1 is 10,000 N.

a. What are the periods of S_2 and S_3?

b. What are the forces on S_2 and S_3?

c. What is the kinetic-energy ratio K_1/K_3 for S_1 and S_3?

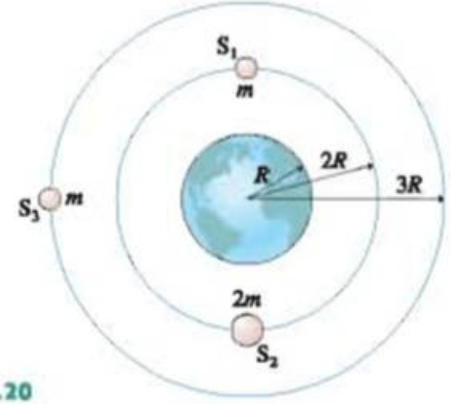


FIGURE EX13.20

2

28. FIGURE P13.28 shows three masses. What are the magnitude and the direction of the net gravitational force on (a) the 20.0 kg mass and (b) the 5.0 kg mass? Give the direction as an angle cw or ccw from the y-axis.

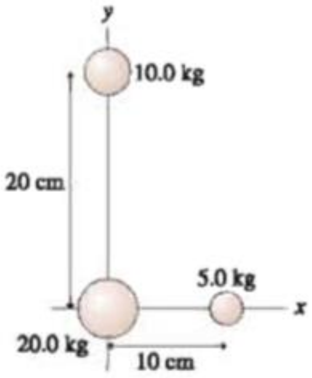


FIGURE P13.28

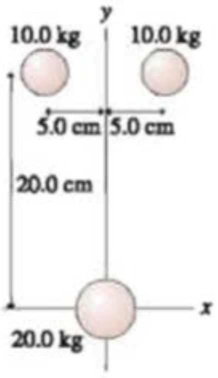


FIGURE P13.29

Materi

75. Let's look in more detail at how a satellite is moved from one circular orbit to another. FIGURE CP13.75 shows two circular orbits, of radii r_1 and r_2, and an elliptical orbit that connects them. Points 1 and 2 are at the ends of the semimajor axis of the ellipse.

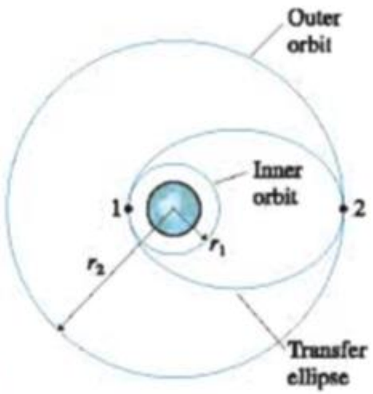


FIGURE CP13.75

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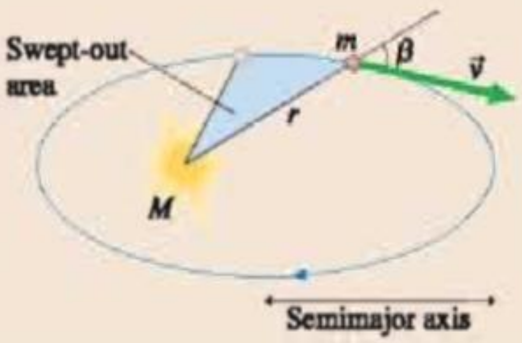
Ringkasan

Orbital motion of a planet (or satellite) is described by **Kepler's laws:**

1. Orbits are ellipses with the sun (or planet) at one focus.
2. A line between the sun and the planet sweeps out equal areas during equal intervals of time.
3. The square of the planet's period T is proportional to the cube of the orbit's semimajor axis.



Circular orbits are a special case of an ellipse. For a circular orbit around a mass M,

$$v = \sqrt{\frac{GM}{r}} \quad \text{and} \quad T^2 = \left(\frac{4\pi^2}{GM}\right)r^3$$

Conservation of angular momentum

The angular momentum $L = mrv\sin\beta$ remains constant throughout the orbit. Kepler's second law is a consequence of this law.

Orbital energetics

A satellite's mechanical energy $E_{mech} = K + U_g$ is conserved, where the gravitational potential energy is

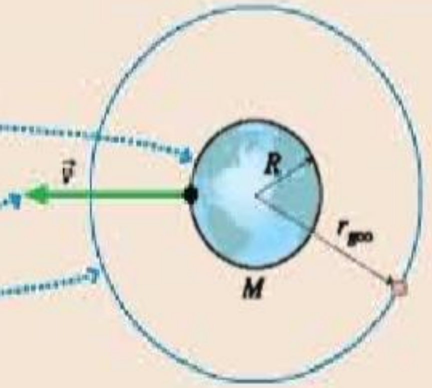
$$U_g = -\frac{GMm}{r}$$

For circular orbits, $K = -\frac{1}{2}U_g$ and $E_{mech} = \frac{1}{2}U_g$. Negative total energy is characteristic of a **bound system.**

Applications

For a planet of mass M and radius R,

- The free-fall acceleration on the surface is $g_{surface} = \dfrac{GM}{R^2}$
- The **escape speed** is $v_{escape} = \sqrt{\dfrac{2GM}{R}}$
- The radius of a **geosynchronous orbit** is $r_{geo} = \left(\dfrac{GM}{4\pi^2}T^2\right)^{1/3}$



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