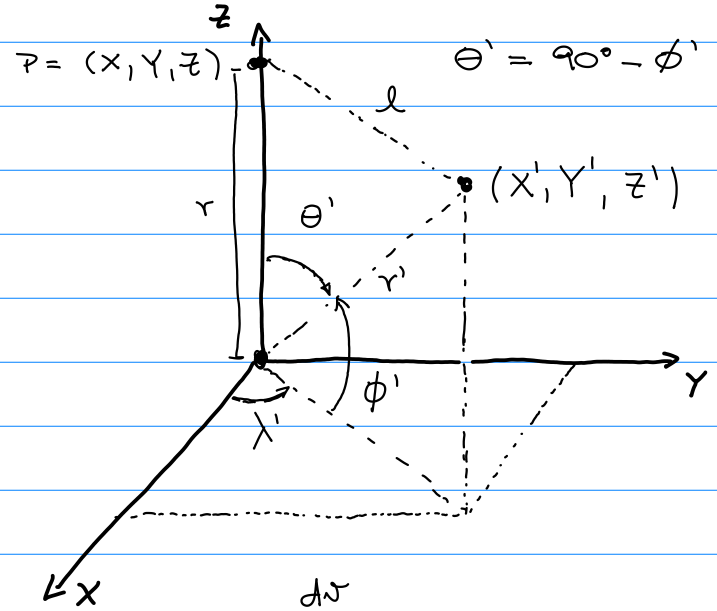
Sphere

$X' = r' \sin\theta' \cos\lambda'$ $\quad$ $X = r \sin\theta \cos\lambda$

$Y' = r' \sin\theta' \sin\lambda'$ $\quad$ $Y = r \sin\theta \sin\lambda$

$Z' = r' \cos\theta'$ $\quad$ $Z = r \cos\theta$



$$\ell = \sqrt{(X-X')^2 + (Y-Y')^2 + (Z-Z')^2}$$

law of cosines $$= \sqrt{r^2 + r'^2 - 2 r r' \cos\theta'}$$

For convenience, consider : $G\rho = 1$

$$U_P = \iiint \frac{1}{\ell}\, dv$$

radius of the sphere

$$= \int_0^R \int_0^\pi \int_0^{2\pi} \frac{1}{\sqrt{r^2 + r'^2 - 2 r r' \cos\theta'}} \underbrace{r'^2 \sin\theta'\, d\lambda'\, d\theta'\, dr'}_{dv}$$

$$= 2\pi \int_0^R r'^2 \int_0^\pi \frac{\sin\theta'}{\sqrt{r^2 + r'^2 - 2 r r' \cos\theta'}}\, d\theta'\, dr'$$

$$\boxed{\begin{aligned} t &= \cos\theta' \\ dt &= -\sin\theta'\, d\theta' \\ \theta' = \pi &\longrightarrow t = -1 \\ \theta' = 0 &\longrightarrow t = 1 \end{aligned}}$$

$$= 2\pi \int_0^R r'^2 \int_{-1}^{1} \frac{1}{\sqrt{r^2 + r'^2 - 2 r r' t}}\, dt\, dr'$$

$$= 2\pi \int_0^R r'^2 \left[- \frac{\sqrt{r^2 + r'^2 - 2 r r' t}}{r r'} \right]_{-1}^{1} dr'$$

$$= 2\pi \int_0^R r'^2 \left[\frac{\sqrt{r^2 + r'^2 + 2 r r'} - \sqrt{r^2 + r'^2 - 2 r r'}}{r r'} \right] dr'$$

$$= 2\pi \int_0^R r' \left[\frac{|r + r'| - |r - r'|}{r} \right] dr'$$

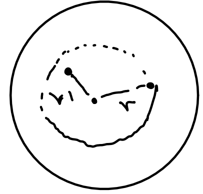
$$|x| = \begin{cases} x, & x > 0 \\ -x, & x < 0 \end{cases}$$

1) $r > R$, $|r + r'| = r + r'$, $|r - r'| = r - r'$

$$U_{out} = 2\pi \frac{1}{r} \int_0^R r'r + r'^2 - r'r + r'^2\, dr' = \int_0^R 2 r'^2\, dr' =$$

$$= 2\pi \frac{1}{r} \left[2 \frac{R^3}{3} \right] = \frac{4\pi}{3} R^3 \frac{1}{r} \qquad \boxed{G\rho = 1}$$

$$\frac{GM}{r}$$



2) $r < R$

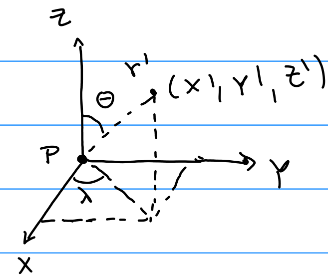
$$U_{IN} = 2\pi \left[\int_0^r \frac{r'}{r} \left(\overbrace{|r+r'|}^{r+r'} - \overbrace{|r-r'|}^{r-r'} \right) dr' + \int_r^R \frac{r'}{r} \left(\overbrace{|r+r'|}^{r+r'} - \overbrace{|r-r'|}^{r'-r} \right) dr' \right]$$

$$= 2\pi \frac{1}{r} \left[\int_0^r 2r'^2 \, dr' + \int_r^R 2r'r \, dr' \right]$$

$$= 2\pi \frac{1}{r} \left[2\frac{r^3}{3} + 2r \left(\frac{R^2}{2} - \frac{r^2}{2} \right) \right]$$

$$= 2\pi \left[\frac{2r^2}{3} + \underbrace{R^2}_{\frac{3}{3}R^2} - r^2 \right] = 2\pi \left(R^2 - \frac{r^2}{3} \right)$$

3) $r = 0 \qquad \ell = r'$

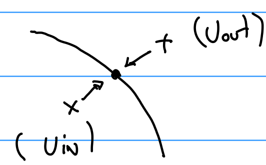


$$U_0 = \iiint \frac{1}{r'} r'^2 \sin\theta \, d\lambda' d\theta' dr'$$

$$= \int_0^R \int_0^\pi \int_0^{2\pi} r' \sin\theta \, d\lambda' d\theta' dr'$$

$$= 2\pi \int_0^R r' \left[-\cos\theta \right]_0^\pi dr' = 2\pi R^2$$

4) $r = R$, $\lim_{r \to R^-} U_{IN} = \lim_{r \to R^+} U_{out} = \frac{4}{3}\pi R^2$



$G\rho = 1$

$$U_P = \begin{cases} \frac{4}{3}\pi R^3 \frac{1}{r}, & r > R \\ \frac{4}{3}\pi R^2, & r = R \\ 2\pi \left(R^2 - \frac{r^2}{3} \right), & r < R \\ 2\pi R^2, & r = 0 \end{cases}$$

(Sansò and Sideris, 2013. p. 10-11)

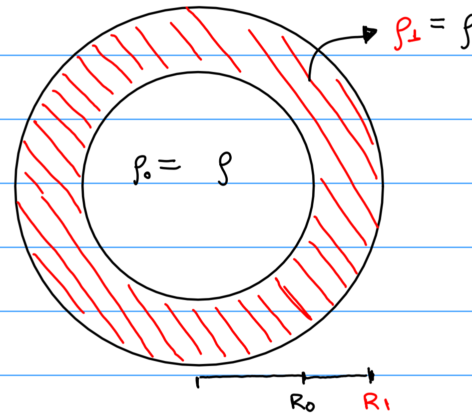
Ex.: Faça um gráfico do potencial gravitacional produzido por uma esfera sólida em função de r.

Ex.: Defina o Laplaciano, primeira e segunda derivadas radiais do potencial produzido por uma esfera sólida.

$r = \sqrt{x^2 + y^2 + z^2}$

$$\partial_{xx}U + \partial_{yy}U + \partial_{zz}U = \nabla^2 U$$

$r > R_1$,



$$U_p = G\frac{4}{3}\pi R_1^3 \rho_1 \frac{1}{r} - G\frac{4}{3}\pi R_0^3 \rho_0 \frac{1}{r}$$

$$= G\frac{4}{3}\pi \rho \left(R_1^3 - R_0^3\right)\frac{1}{r}$$

$R_0 < r < R_1$

$$U_p = G\,2\pi \rho_1 \left(R_1^2 - \frac{r^2}{3}\right) - G\frac{4}{3}\pi R_0^3 \rho_0 \frac{1}{r}$$

$$= G\,2\pi \rho \left(R_1^2 - \frac{r^2}{3} - \frac{2}{3}\frac{R_0^3}{r}\right)$$

$r < R_0$

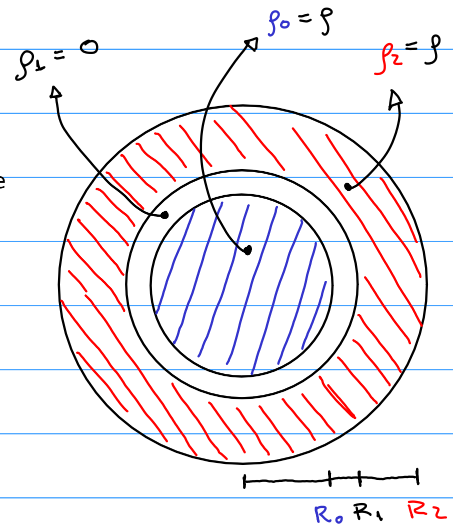
$$U_p = G\,2\pi \left(R_1^2 - \frac{r^2}{3}\right)\rho_1 - G\,2\pi\left(R_0^2 - \frac{r^2}{3}\right)\rho_0$$

$$= G\,2\pi \rho \left(R_1^2 - R_0^2\right)$$

Ex.: Faça um gráfico do potencial gravitacional produzido por uma casca esférica em função de r.

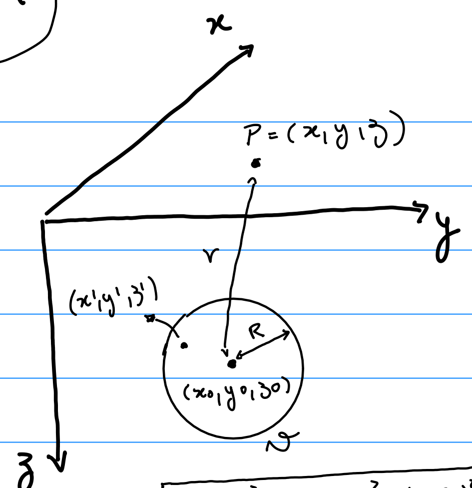
Ex.: Defina o Laplaciano, primeira e segunda derivadas radiais do potential produzido por uma cascas esférica.

Ex.: Defina o potencial, Laplaciano, primeira e segunda derivadas radiais produzidos pelo modelo de esféricas concêntricas.



Ex.: Faça um gráfico do potencial gravitacional produzido pelo modelo de esferas concêntricas em função de r.

$$\boxed{\mathbf{B}/\mu_0 = \mathbf{H}}$$



Now, consider a solid sphere with radius R, volume v and center at the coordinates (x_0, y_0, z_0) referred to a topocentric Catesian system.

Consider also that there is a constant magnetic intensity field $\mathbf{H}_0$

The magnetic intensity produced by this sphere at a point P is given by:

inside or outside

derivatives with respect to the coordinates x, y, z

$$\mathbf{H}_P = \mathbf{H}_0 - \nabla \Gamma_P$$

(Stratton, 2007, p. 228; Reitz and Milford, 1960, p. 189)

$$r = \sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2}$$

$$\ell = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}$$

$$\Gamma_P = -\frac{1}{4\pi} \iiint_v \mathbf{h}(x', y', z')^T \, \nabla \frac{1}{\ell} \, dv$$

resultant magnetic intensity field inside the sphere

Consider a uniform magnetization given by $\mathbf{h} = \boldsymbol{\chi} \mathbf{H}^*$

$$\Gamma_P = -\frac{1}{4\pi} \iiint_v (\boldsymbol{\chi} \mathbf{H}^*)^T \, \nabla \frac{1}{\ell} \, dv = -\nabla \Psi_P^T \boldsymbol{\chi} \mathbf{H}^* , \quad \Psi_P = \frac{1}{4\pi} \iiint_v \frac{1}{\ell} \, dv$$

$$\nabla \Gamma_P = -\nabla^2 \Psi_P \boldsymbol{\chi} \mathbf{H}^* , \quad \mathbf{H}_P = \mathbf{H}_0 + \nabla^2 \Psi_P \boldsymbol{\chi} \mathbf{H}^*$$

Consider a point P inside the sphere $(\mathbf{H}^* = \mathbf{H}_P)$

$$\mathbf{H}_P - \nabla^2 \Psi_P \boldsymbol{\chi} \mathbf{H}_P = \mathbf{H}_0$$

$$\mathbf{H}_P = (\mathbf{I} - \nabla^2 \Psi_P \boldsymbol{\chi})^{-1} \mathbf{H}_0$$

$$\mathbf{h} = \boldsymbol{\chi} \overbrace{(\mathbf{I} - \nabla^2 \Psi_P \boldsymbol{\chi})^{-1} \mathbf{H}_0}^{\mathbf{H}_P}$$

$$= (\mathbf{I} - \boldsymbol{\chi} \nabla^2 \Psi_P)^{-1} \boldsymbol{\chi} \mathbf{H}_0$$

(Searle, 1982, p. 151)

(see the potential U_{in}) $\rightarrow \quad \Psi_P = \left(\frac{1}{4\pi}\right) 2\pi \left(R^2 - \frac{r^2}{3}\right)$,

$$\partial_x \Psi_P = -\left(\frac{1}{4\pi}\right) \frac{4\pi (x - x_0)}{3}$$

$$\partial_{xx} \Psi_P = -\left(\frac{1}{4\pi}\right) \frac{4\pi}{3}$$

$$\partial_{xy} \Psi_P = 0$$

$$\nabla^2 \Psi_P = -\frac{1}{3} \mathbf{I}$$

Consider a constant isotropic susceptibility $\boldsymbol{\chi} = \chi \mathbf{I}$

$$\mathbf{h} = \left(\mathbf{I} + \frac{1}{3} \chi \mathbf{I}\right)^{-1} \chi \mathbf{H}_0$$

$$\boxed{p/ \ \chi \ll 1 \quad \tilde{\mathbf{h}} = \chi \mathbf{H}_0}$$

See the notebooks sphere.ipynb and demagnetization_sphere.ipynb

Ex: $\Delta \mathbf{h} = \|\mathbf{h}\|_2 - \|\tilde{\mathbf{h}}\|_2$

$\Delta \mathbf{h} \quad \times \quad \chi \rightarrow 10^{-5} - 1$

Searle, S. R., (1982). Matrix Algebra Useful for Statistics, Wiley-Interscience, ISBN: 0-471-86681-4
Stratton, J. A. (2007). Electromagnetic Theory, Wiley-IEEE Press, reissue Edn. ISBN: 0-470-13153-5
Reitz, J. R., and Milford, F. J. (1960). Foundations of Electromagnetic Theory, Addison Wesley, 4 Edn.