

PHY 711 Classical Mechanics and Mathematical Methods

10-10:50 AM MWF in Olin 103

Notes for Lecture 38

**Starting course review; revisiting
physics analyzed in accelerated
coordinate frames – Chap 2 F&W**

- 1. Angular acceleration**
- 2. Linear and angular acceleration**
- 3. Foucault pendulum**

35	Fri, 11/15/2024	Chap. 12	Viscous effects in hydrodynamics	#28
36	Mon, 11/18/2024	Chap. 12	Viscous effects in hydrodynamics	#29
37	Wed, 11/20/2024	Chap. 13	Elasticity	#30
38	Fri, 11/22/2024	Chap. 1-13	Review	
39	Mon, 11/25/2024	Chap. 1-13	Review	
	Wed, 11/27/2024	Thanksgiving		
	Fri, 11/29/2024	Thanksgiving		
	Mon, 12/02/2024		Presentations 1	
	Wed, 12/04/2024		Presentations 2	
40	Fri, 12/06/2024	Chap. 1-13	Review	

**PHY 711 Presentation Schedule
Fall 2024**

Monday 12/02/2024

	Presenter Name	Topic
10:00-10:24	Thomas Myers	Velocity Dependent forces in lagrangian mechanics
10:26-10:50	Bhargava Ramachandrappa	Lambert W function and the Damped Harmonic Oscillator Problem

Wednesday 12/04/2024

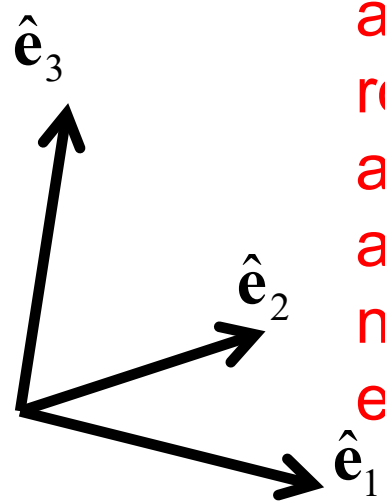
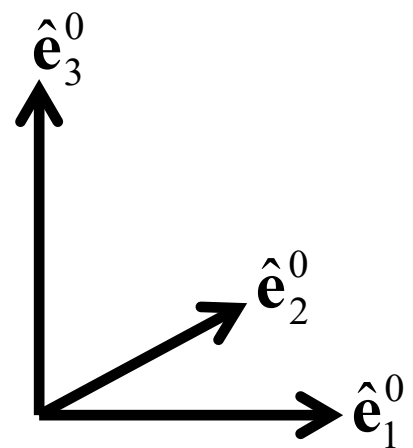
	Presenter Name	Topic
10:00-10:24	Julia Radtke	
10:26-10:50	Conall O'Leary	



Physical laws as described in non-inertial coordinate systems

- Newton's laws are formulated in an inertial frame of reference $\{\hat{\mathbf{e}}_i^0\}$
- For some problems, it is convenient to transform the the equations into a non-inertial coordinate system

$$\{\hat{\mathbf{e}}_i(t)\}$$



Note that in addition to rotation, linear acceleration can also contribute to non-inertial effects.

Comparison of analysis in “inertial frame” versus “non-inertial frame”

Denote by $\hat{\mathbf{e}}_i^0$ an fixed coordinate system in 3 orthogonal directions

Denote by $\hat{\mathbf{e}}_i$ a moving coordinate system in 3 orthogonal directions

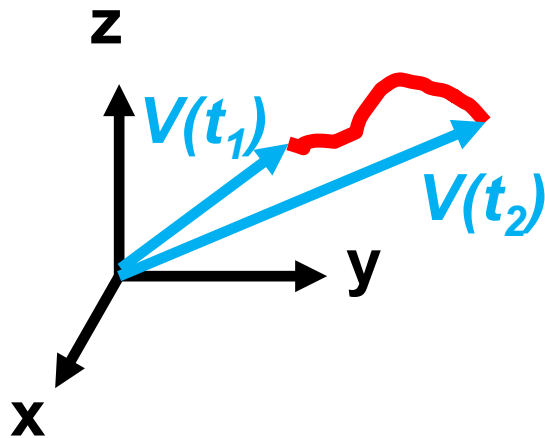
$$\mathbf{V} = \sum_{i=1}^3 V_i^0 \hat{\mathbf{e}}_i^0 = \sum_{i=1}^3 V_i \hat{\mathbf{e}}_i$$

$$\left(\frac{d\mathbf{V}}{dt} \right)_{inertial} = \sum_{i=1}^3 \frac{dV_i^0}{dt} \hat{\mathbf{e}}_i^0 = \sum_{i=1}^3 \frac{dV_i}{dt} \hat{\mathbf{e}}_i + \sum_{i=1}^3 V_i \frac{d\hat{\mathbf{e}}_i}{dt}$$

Define: $\left(\frac{d\mathbf{V}}{dt} \right)_{body} \equiv \sum_{i=1}^3 \frac{dV_i}{dt} \hat{\mathbf{e}}_i$ **This represents the time rate of change of V measured within the e frame.**

$$\Rightarrow \left(\frac{d\mathbf{V}}{dt} \right)_{inertial} = \left(\frac{d\mathbf{V}}{dt} \right)_{body} + \sum_{i=1}^3 V_i \frac{d\hat{\mathbf{e}}_i}{dt}$$

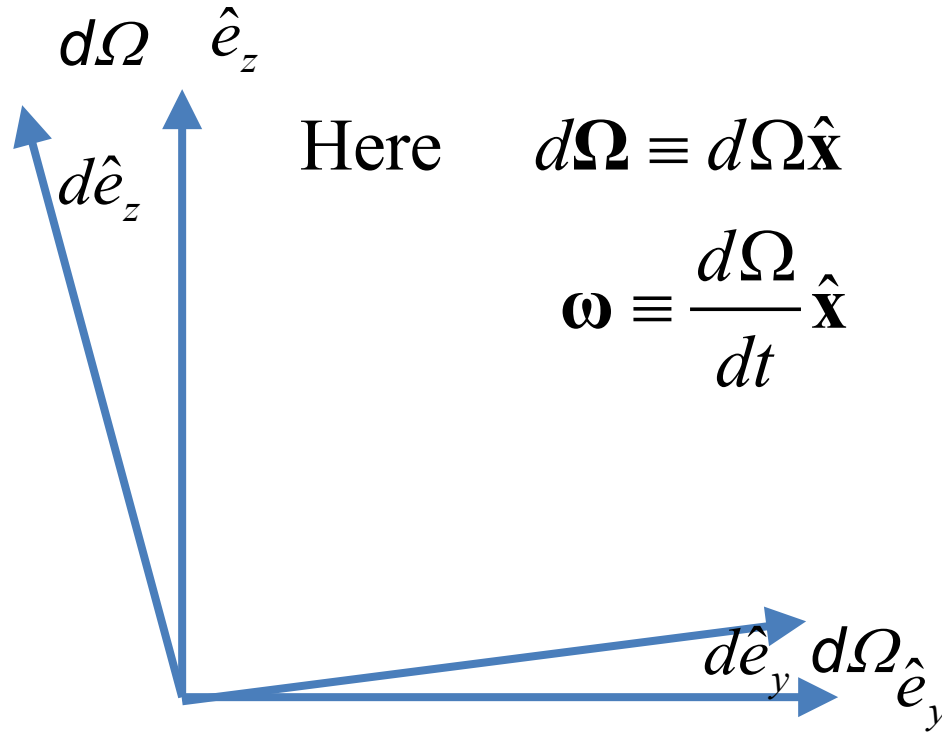
e^0 example



$$\frac{d\mathbf{V}(t)}{dt} = \frac{dV_x^0(t)}{dt} \hat{\mathbf{x}} + \frac{dV_y^0(t)}{dt} \hat{\mathbf{y}} + \frac{dV_z^0(t)}{dt} \hat{\mathbf{z}}$$

e example – same motion described in moving coordinate system.

Properties of the frame motion (rotation only):



Here $d\Omega \equiv d\Omega \hat{\mathbf{x}}$

$$\boldsymbol{\omega} \equiv \frac{d\Omega}{dt} \hat{\mathbf{x}}$$

$$d\hat{e}_y = d\Omega \hat{e}_z$$

$$d\hat{e}_z = -d\Omega \hat{e}_y$$

$$\Rightarrow d\hat{\mathbf{e}} = d\Omega \times \hat{\mathbf{e}}$$

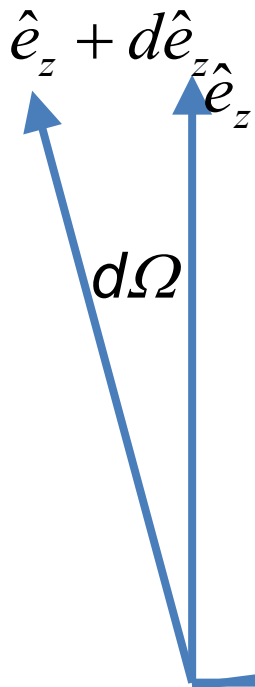
$$\frac{d\hat{\mathbf{e}}}{dt} = \frac{d\Omega}{dt} \times \hat{\mathbf{e}}$$

$$\frac{d\hat{\mathbf{e}}}{dt} = \boldsymbol{\omega} \times \hat{\mathbf{e}}$$

Note that the coordinate \hat{e}_x is pointing out of the screen.

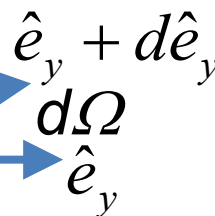


Properties of the frame motion (rotation only):



$$d\hat{e} = d\Omega \times \hat{e} \quad \frac{d\hat{e}}{dt} = \frac{d\Omega}{dt} \times \hat{e} \quad \frac{d\hat{e}}{dt} = \boldsymbol{\omega} \times \hat{e}$$

Note that \hat{e}_x is pointing out of the screen.



Rotation about x-axis:

rotation matrix

$$\begin{pmatrix} e_y \\ e_z \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} e_y \\ e_z \end{pmatrix} \quad \begin{pmatrix} e_y + de_y \\ e_z + de_z \end{pmatrix} = \begin{pmatrix} \cos(d\Omega) & \sin(d\Omega) \\ -\sin(d\Omega) & \cos(d\Omega) \end{pmatrix} \begin{pmatrix} e_y \\ e_z \end{pmatrix}$$

$$\begin{pmatrix} de_y \\ de_z \end{pmatrix} = \begin{pmatrix} \cos(d\Omega) - 1 & \sin(d\Omega) \\ -\sin(d\Omega) & \cos(d\Omega) - 1 \end{pmatrix} \begin{pmatrix} e_y \\ e_z \end{pmatrix} \approx \begin{pmatrix} 0 & d\Omega \\ -d\Omega & 0 \end{pmatrix} \begin{pmatrix} e_y \\ e_z \end{pmatrix}$$

More details

Rotation about x -axis:

$$\begin{pmatrix} e_y \\ e_z \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} e_y \\ e_z \end{pmatrix} \quad \begin{pmatrix} e_y + de_y \\ e_z + de_z \end{pmatrix} = \begin{pmatrix} \cos(d\Omega) & \sin(d\Omega) \\ -\sin(d\Omega) & \cos(d\Omega) \end{pmatrix} \begin{pmatrix} e_y \\ e_z \end{pmatrix}$$

$$\begin{pmatrix} de_y \\ de_z \end{pmatrix} = \begin{pmatrix} \cos(d\Omega) - 1 & \sin(d\Omega) \\ -\sin(d\Omega) & \cos(d\Omega) - 1 \end{pmatrix} \begin{pmatrix} e_y \\ e_z \end{pmatrix} \approx \begin{pmatrix} 0 & d\Omega \\ -d\Omega & 0 \end{pmatrix} \begin{pmatrix} e_y \\ e_z \end{pmatrix}$$

$$e_y + de_y = \cos(d\Omega)e_y + \sin(d\Omega)e_z$$

$$e_z + de_z = -\sin(d\Omega)e_y + \cos(d\Omega)e_z$$

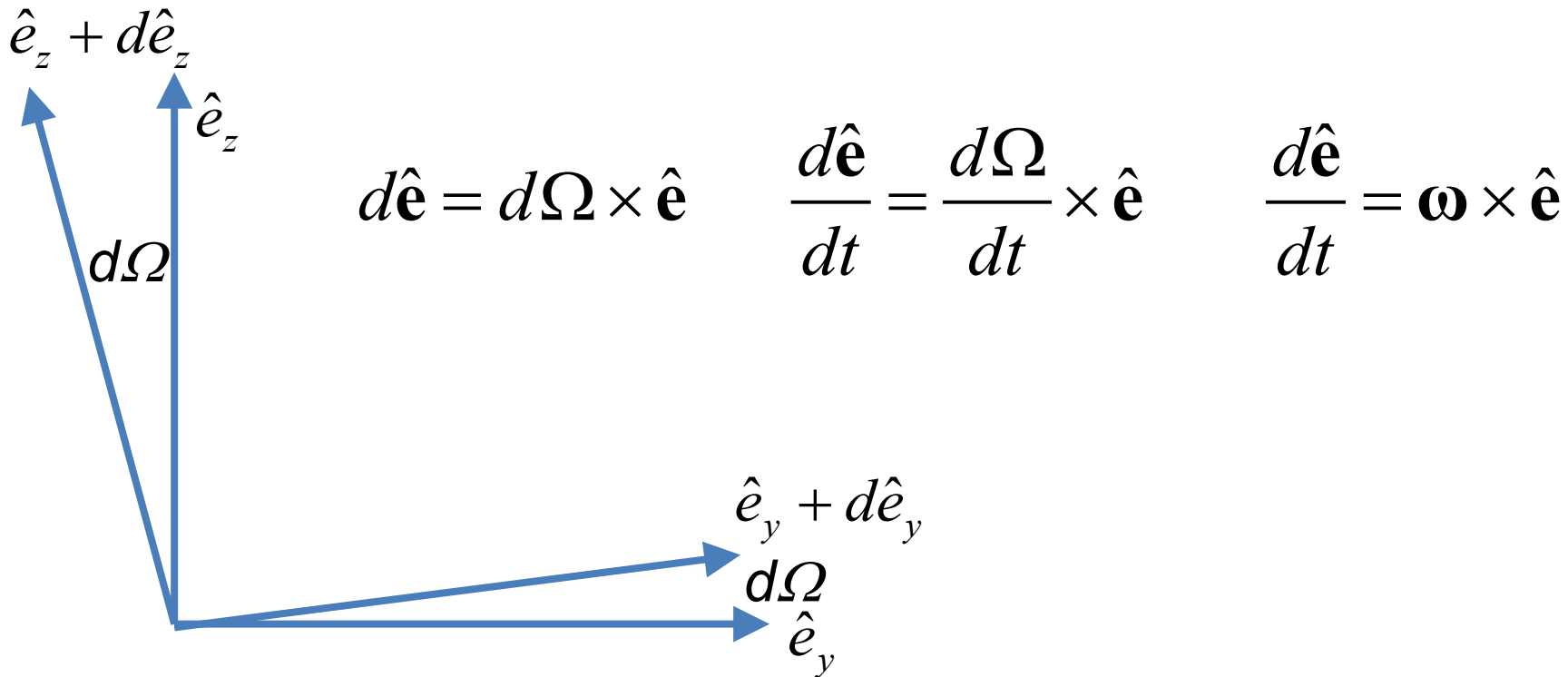
Taylor's series

$$f(x_0 + dx) = f(x_0) + dx \left. \frac{df}{dx} \right|_{x_0} + \frac{1}{2} (dx)^2 \left. \frac{d^2 f}{dx^2} \right|_{x_0} + \dots$$

$$\sin(dx) = dx - \frac{1}{6} (dx)^3 \dots \approx dx \quad \cos(dx) = 1 - \frac{1}{2} (dx)^2 \dots \approx 1$$



Properties of the frame motion (rotation only):



Rotation about x -axis:

$$\begin{pmatrix} de_y \\ de_z \end{pmatrix} \approx \begin{pmatrix} 0 & d\Omega \\ -d\Omega & 0 \end{pmatrix} \begin{pmatrix} e_y \\ e_z \end{pmatrix} = d\Omega e_z \hat{\mathbf{y}} - d\Omega e_y \hat{\mathbf{z}} = d\Omega \hat{\mathbf{x}} \times \hat{\mathbf{e}}$$

Define axial vectors $\mathbf{d}\boldsymbol{\Omega} \equiv d\Omega \hat{\mathbf{x}}$ also $\boldsymbol{\omega} = \omega \hat{\mathbf{x}}$

Properties of the frame motion (rotation only) -- continued

$$\left(\frac{d\mathbf{V}}{dt}\right)_{inertial} = \left(\frac{d\mathbf{V}}{dt}\right)_{body} + \sum_{i=1}^3 V_i \frac{d\hat{\mathbf{e}}_i}{dt}$$

$$\left(\frac{d\mathbf{V}}{dt}\right)_{inertial} = \left(\frac{d\mathbf{V}}{dt}\right)_{body} + \boldsymbol{\omega} \times \mathbf{V} = \left(\left(\frac{d}{dt}\right)_{body} + \boldsymbol{\omega} \times \right) \mathbf{V}$$

Effects on 2nd time derivative -- acceleration (rotation only):

$$\left(\frac{d}{dt} \frac{d\mathbf{V}}{dt}\right)_{inertial} = \left(\left(\frac{d}{dt}\right)_{body} + \boldsymbol{\omega} \times \right) \left\{ \left(\frac{d\mathbf{V}}{dt}\right)_{body} + \boldsymbol{\omega} \times \mathbf{V} \right\}$$

$$\left(\frac{d^2\mathbf{V}}{dt^2}\right)_{inertial} = \left(\frac{d^2\mathbf{V}}{dt^2}\right)_{body} + 2\boldsymbol{\omega} \times \left(\frac{d\mathbf{V}}{dt}\right)_{body} + \frac{d\boldsymbol{\omega}}{dt} \times \mathbf{V} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{V}$$

Application of Newton's laws in a coordinate system which has an angular velocity $\boldsymbol{\omega}$ and linear acceleration \mathbf{a} (Here we generalize previous case to add linear acceleration \mathbf{a} .)

Newton's laws; Let \mathbf{r} denote the position of particle of mass m :

$$m \left(\frac{d^2 \mathbf{r}}{dt^2} \right)_{inertial} = \mathbf{F}_{ext}$$

$$m \left(\frac{d^2 \mathbf{r}}{dt^2} \right)_{inertial} = m \left(\mathbf{a} + \left(\frac{d^2 \mathbf{r}}{dt^2} \right)_{body} + 2\boldsymbol{\omega} \times \left(\frac{d\mathbf{r}}{dt} \right)_{body} + \frac{d\boldsymbol{\omega}}{dt} \times \mathbf{r} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r} \right) = \mathbf{F}_{ext}$$

Rearranging to find the effective acceleration within the non-inertial frame --

$$m \left(\frac{d^2 \mathbf{r}}{dt^2} \right)_{body} = \mathbf{F}_{ext} - m\mathbf{a} - 2m\boldsymbol{\omega} \times \left(\frac{d\mathbf{r}}{dt} \right)_{body} - m \frac{d\boldsymbol{\omega}}{dt} \times \mathbf{r} - m\boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}$$

↑
Coriolis
force

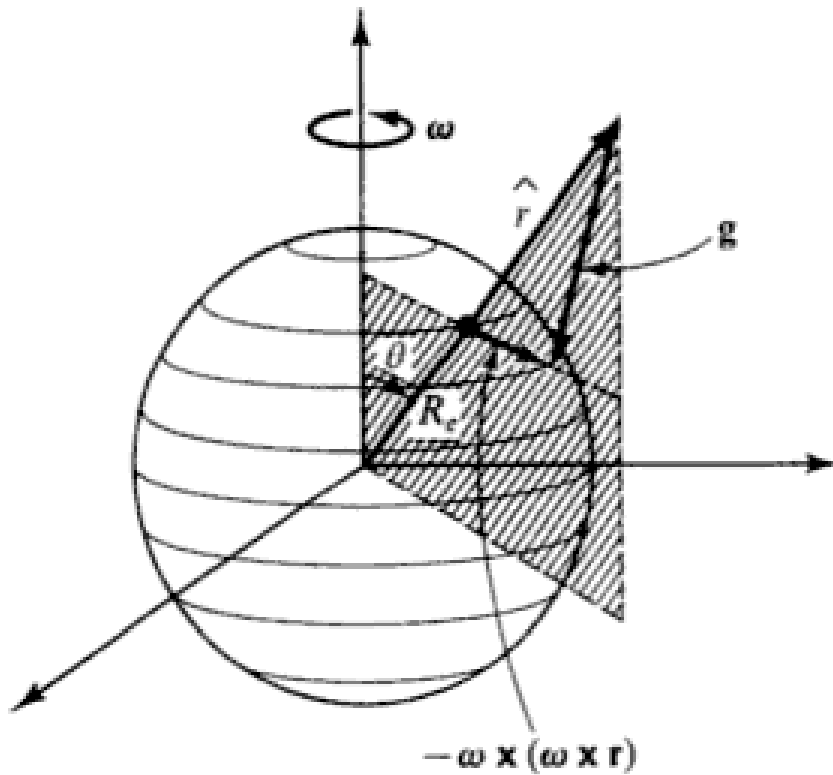
↑
Centrifugal
force

Have you ever experienced any of these “fictitious” forces?

Examples –

1. Playing on a swing
2. Playing on a merry-go-round
3. Riding on a roller coaster
4. Sitting on the surface of the earth
5. Astronaut aboard the International Space Station
6. ???

Motion on the surface of the Earth:



$$\omega = \frac{2\pi}{\tau} \approx 7.3 \times 10^{-5} \text{ rad/s}$$

$$\mathbf{F}_{ext} = -\frac{GM_e m}{r^2} \hat{\mathbf{r}} + \mathbf{F}'$$

Earth's gravity

Support force

Main contributions:

$$m \left(\frac{d^2 \mathbf{r}}{dt^2} \right)_{earth} = -\frac{GM_e m}{r^2} \hat{\mathbf{r}} + \mathbf{F}' - 2m\boldsymbol{\omega} \times \left(\frac{d\mathbf{r}}{dt} \right)_{earth} - m \frac{d\boldsymbol{\omega}}{dt} \times \mathbf{r} - m\boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}$$

Non-inertial effects on effective gravitational “constant”

$$m \left(\frac{d^2 \mathbf{r}}{dt^2} \right)_{\text{earth}} = -\frac{GM_e m}{r^2} \hat{\mathbf{r}} + \mathbf{F}' - 2m\boldsymbol{\omega} \times \left(\frac{d\mathbf{r}}{dt} \right)_{\text{earth}} - m \frac{d\boldsymbol{\omega}}{dt} \times \mathbf{r} - m\boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}$$

For $\left(\frac{d\mathbf{r}}{dt} \right)_{\text{earth}} = 0$ and $\left(\frac{d^2 \mathbf{r}}{dt^2} \right)_{\text{earth}} = 0$,

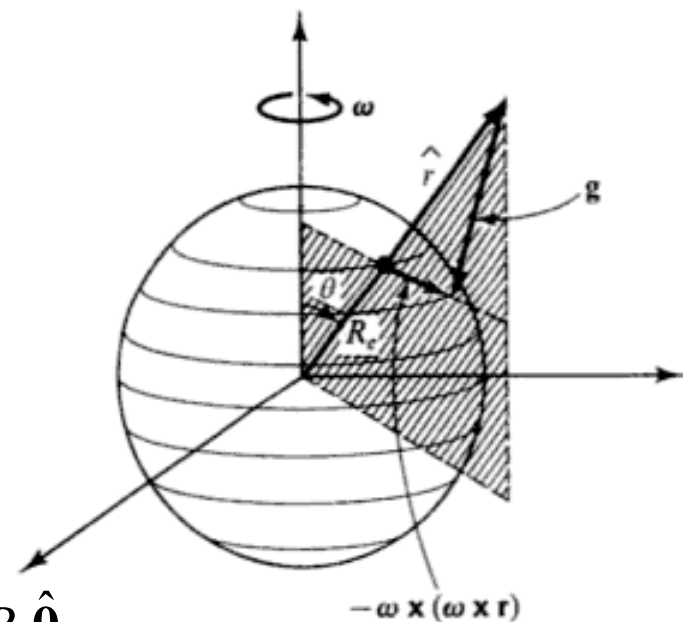
$$0 = -\frac{GM_e m}{r^2} \hat{\mathbf{r}} + \mathbf{F}' - m\boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}$$

$$\mathbf{F}' = -m\mathbf{g}$$

$$\Rightarrow \mathbf{g} = -\frac{GM_e}{r^2} \hat{\mathbf{r}} - \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r} \Big|_{r \approx R_e}$$

$$= \left(-\frac{GM_e}{R_e^2} + \omega^2 R_e \sin^2 \theta \right) \hat{\mathbf{r}} + \sin \theta \cos \theta \omega^2 R_e \hat{\boldsymbol{\theta}}$$

↑ ↑
 9.80 m/s² 0.03 m/s²



Note that in the previous analysis we left out the term $-m \frac{d\boldsymbol{\omega}}{dt} \times \mathbf{r}$

Is this justified?

1. Yes
2. No

According to Google – the rate of rotation of the earth has changed during its existence....

<https://www.discovermagazine.com/planet-earth/the-earths-rotation-is-gradually-slowing-down>



Foucault pendulum

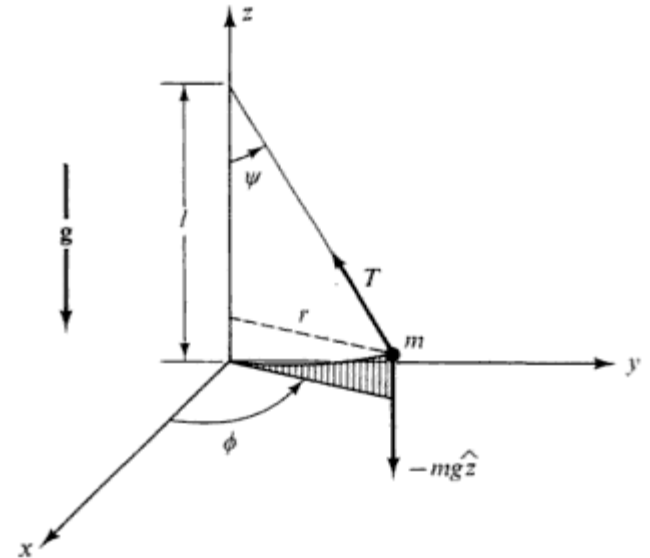
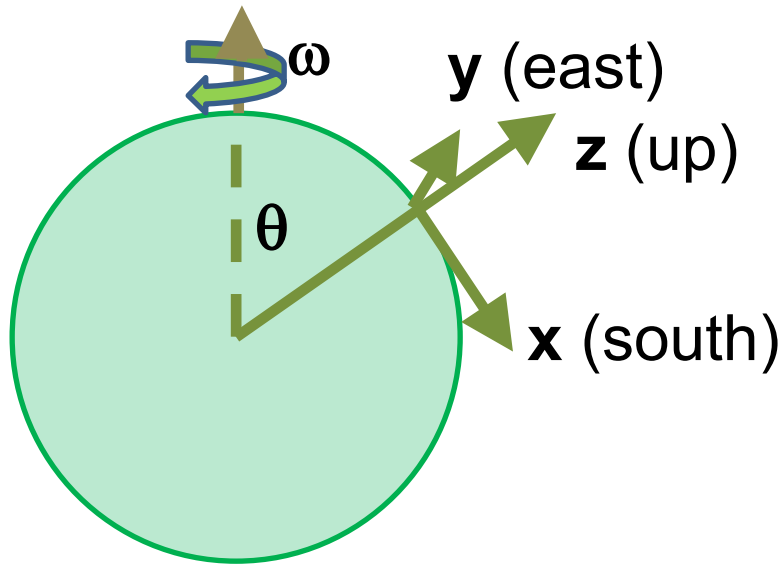
http://www.si.edu/Encyclopedia_SI/nmah/pendulum.htm



The Foucault pendulum was displayed for many years in the Smithsonian's National Museum of American History. It is named for the French physicist Jean Foucault who first used it in 1851 to demonstrate the rotation of the earth.

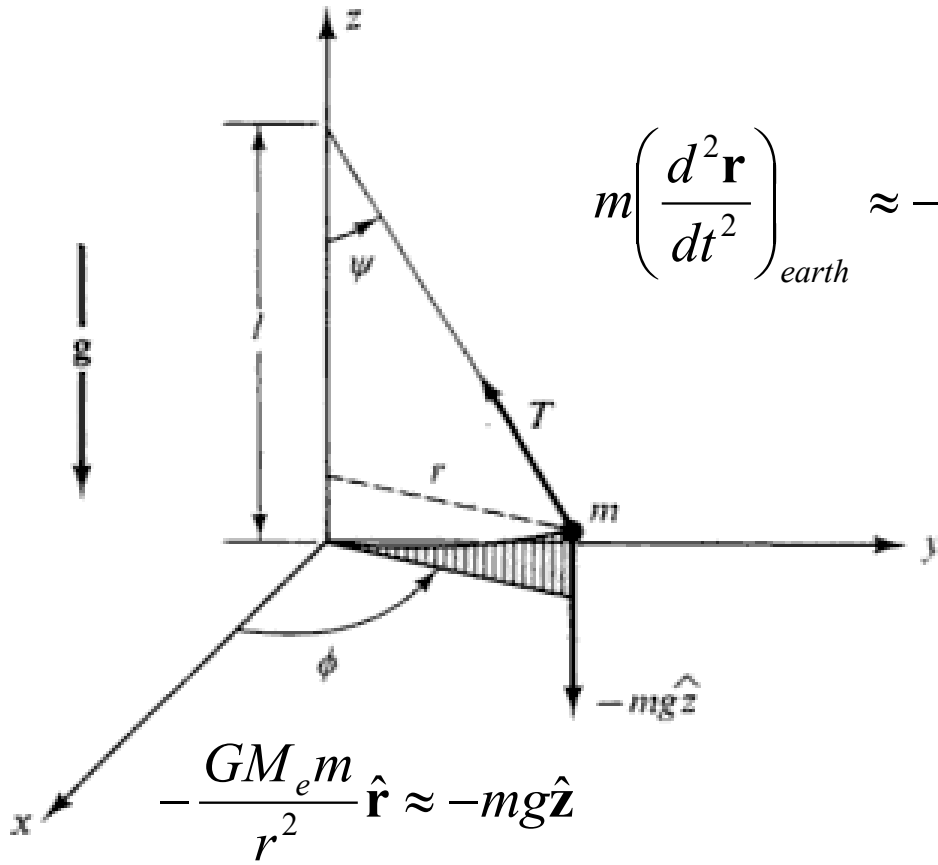
Equation of motion on Earth's surface

$$m \left(\frac{d^2 \mathbf{r}}{dt^2} \right)_{\text{earth}} = -\frac{GM_e m}{r^2} \hat{\mathbf{r}} + \mathbf{F}' - 2m\boldsymbol{\omega} \times \left(\frac{d\mathbf{r}}{dt} \right)_{\text{earth}} - m \frac{d\boldsymbol{\omega}}{dt} \times \mathbf{r} - m\boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}$$

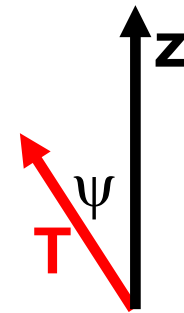


$$\boldsymbol{\omega} \approx -\omega \sin \theta \hat{\mathbf{x}} + \omega \cos \theta \hat{\mathbf{z}}$$

Foucault pendulum continued – keeping leading terms:



$$m \left(\frac{d^2 \mathbf{r}}{dt^2} \right)_{\text{earth}} \approx -\frac{GM_e m}{R_e^2} \hat{\mathbf{r}} + \mathbf{F}' - 2m\boldsymbol{\omega} \times \left(\frac{d\mathbf{r}}{dt} \right)_{\text{earth}}$$



$$-\frac{GM_e m}{r^2} \hat{\mathbf{r}} \approx -mg\hat{\mathbf{z}}$$

$$\mathbf{F}' \approx -T \sin \psi \cos \phi \hat{\mathbf{x}} - T \sin \psi \sin \phi \hat{\mathbf{y}} + T \cos \psi \hat{\mathbf{z}}$$

$$\boldsymbol{\omega} \approx -\omega \sin \theta \hat{\mathbf{x}} + \omega \cos \theta \hat{\mathbf{z}}$$

$$\boldsymbol{\omega} \times \left(\frac{d\mathbf{r}}{dt} \right)_{\text{earth}} \approx \omega (-\dot{y} \cos \theta \hat{\mathbf{x}} + (\dot{x} \cos \theta + \dot{z} \sin \theta) \hat{\mathbf{y}} - \dot{y} \sin \theta \hat{\mathbf{z}})$$

Some details --

$$\boldsymbol{\omega} \approx -\omega \sin \theta \hat{\mathbf{x}} + \omega \cos \theta \hat{\mathbf{z}}$$

$$\boldsymbol{\omega} \times \left(\frac{d\mathbf{r}}{dt} \right)_{\text{earth}} = \begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ -\omega \sin \theta & 0 & \omega \cos \theta \\ \dot{x} & \dot{y} & \dot{z} \end{vmatrix}$$

$$\boldsymbol{\omega} \times \left(\frac{d\mathbf{r}}{dt} \right)_{\text{earth}} \approx \omega \left(-\dot{y} \cos \theta \hat{\mathbf{x}} + (\dot{x} \cos \theta + \dot{z} \sin \theta) \hat{\mathbf{y}} - \dot{y} \sin \theta \hat{\mathbf{z}} \right)$$

Foucault pendulum continued – keeping leading terms:

$$m \left(\frac{d^2 \mathbf{r}}{dt^2} \right)_{\text{earth}} \approx -\frac{GM_e m}{R_e^2} \hat{\mathbf{r}} + \mathbf{F}' - 2m\boldsymbol{\omega} \times \left(\frac{d\mathbf{r}}{dt} \right)_{\text{earth}}$$

$$m\ddot{x} \approx -T \sin \psi \cos \phi + 2m\omega \dot{y} \cos \theta$$

$$m\ddot{y} \approx -T \sin \psi \sin \phi - 2m\omega (\dot{x} \cos \theta + \dot{z} \sin \theta)$$

$$m\ddot{z} \approx T \cos \psi - mg + 2m\omega \dot{y} \sin \theta$$

Further approximation :

$$\psi \ll 1; \quad \ddot{z} \approx 0; \quad T \approx mg$$

$$m\ddot{x} \approx -mg \sin \psi \cos \phi + 2m\omega \dot{y} \cos \theta$$

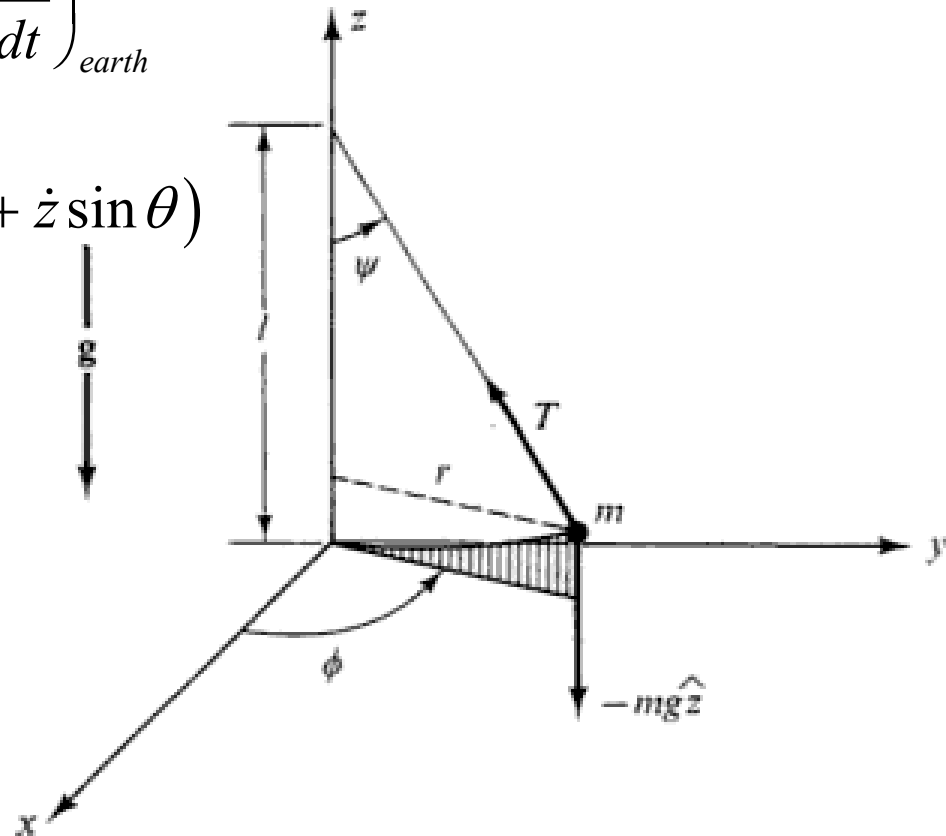
$$m\ddot{y} \approx -mg \sin \psi \sin \phi - 2m\omega \dot{x} \cos \theta$$

Also note that :

$$x \approx \ell \sin \psi \cos \phi$$

$$y \approx \ell \sin \psi \sin \phi$$

ℓ denotes the length of the rope/wire



Foucault pendulum continued – coupled equations:

$$\ddot{x} \approx -\frac{g}{\ell} x + 2\omega \cos \theta \dot{y}$$

$$\ddot{y} \approx -\frac{g}{\ell} y - 2\omega \cos \theta \dot{x}$$

Try to find a solution of the form :

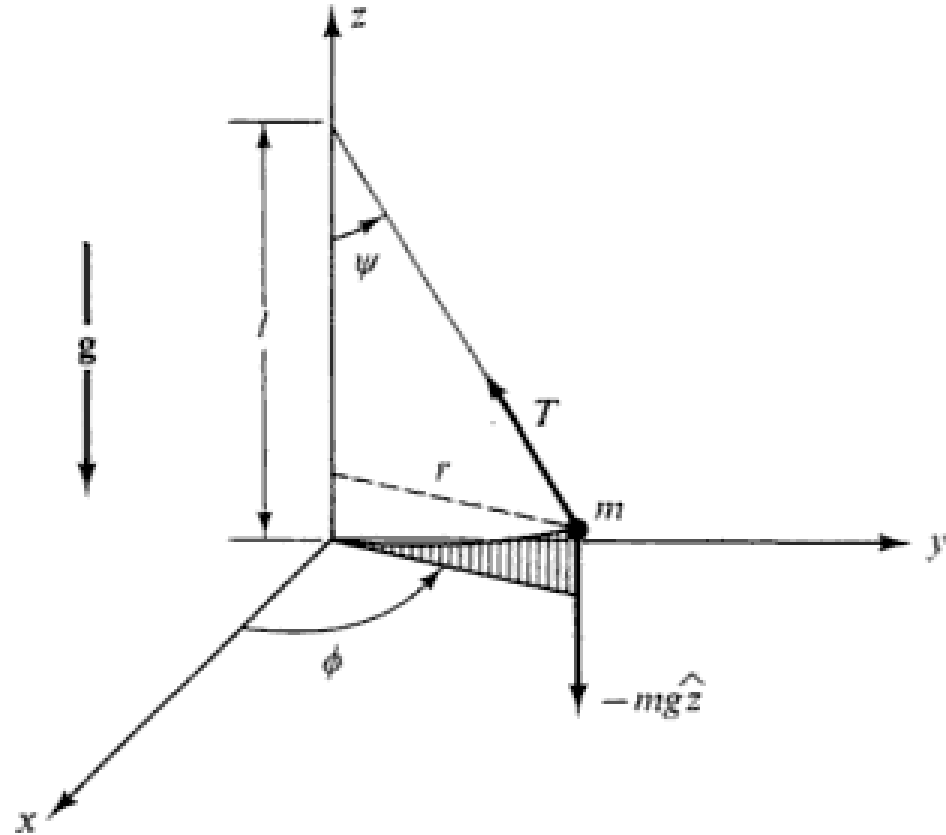
$$x(t) = X e^{-iqt} \quad y(t) = Y e^{-iqt}$$

Denote $\omega_{\perp} \equiv \omega \cos \theta$

$$\begin{pmatrix} -q^2 + \frac{g}{\ell} & i2\omega_{\perp}q \\ -i2\omega_{\perp}q & -q^2 + \frac{g}{\ell} \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = 0$$

Non - trivial solutions :

$$q_{\pm} = \alpha \pm \beta \equiv \omega_{\perp} \pm \sqrt{\omega_{\perp}^2 + \frac{g}{\ell}}$$





Foucault pendulum continued – coupled equations:

Solution continued :

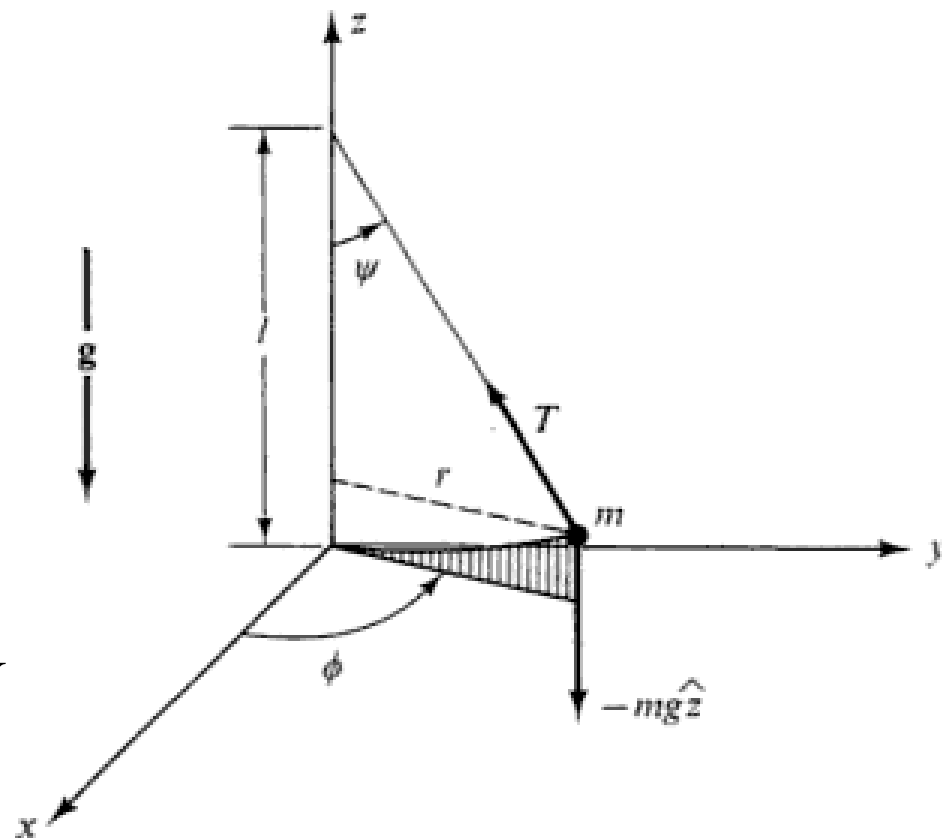
$$x(t) = Xe^{-iqt} \quad y(t) = Ye^{-iqt}$$

$$\begin{pmatrix} -q^2 + \frac{g}{\ell} & i2\omega_{\perp}q \\ -i2\omega_{\perp}q & -q^2 + \frac{g}{\ell} \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = 0$$

Non - trivial solutions :

$$q_{\pm} = \alpha \pm \beta \equiv \omega_{\perp} \pm \sqrt{\omega_{\perp}^2 + \frac{g}{\ell}}$$

Amplitude relationship : $X = iY$



General solution with complex amplitudes C and D :

$$x(t) = \text{Re}\{iCe^{-i(\alpha+\beta)t} + iDe^{-i(\alpha-\beta)t}\}$$

$$y(t) = \text{Re}\{Ce^{-i(\alpha+\beta)t} + De^{-i(\alpha-\beta)t}\}$$

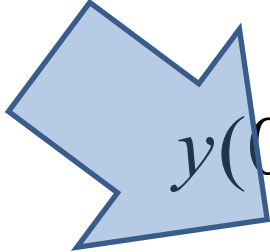
General solution with complex amplitudes C and D :

$$x(t) = \text{Re} \left\{ iC e^{-i(\alpha+\beta)t} + iD e^{-i(\alpha-\beta)t} \right\}$$

$$y(t) = \text{Re} \left\{ C e^{-i(\alpha+\beta)t} + D e^{-i(\alpha-\beta)t} \right\}$$

$$q_{\pm} = \alpha \pm \beta \equiv \omega_{\perp} \pm \sqrt{\omega_{\perp}^2 + \frac{g}{\ell}} \approx \omega_{\perp} \pm \sqrt{\frac{g}{\ell}}$$

since $\omega_{\perp} \approx 7 \times 10^{-5} \cos \theta \text{ rad / s} \ll \sqrt{\frac{g}{\ell}}$

Suppose: $x(0) = X_0$  $y(0) = 0$

$$x(t) = X_0 \cos\left(\sqrt{\frac{g}{\ell}}t\right) \cos(\omega_{\perp}t)$$

Note that

$$\omega = \frac{2\pi}{24 \cdot 3600 \text{ s}} = 7 \times 10^{-5} \text{ rad/sec}$$

$$y(t) = -X_0 \cos\left(\sqrt{\frac{g}{\ell}}t\right) \sin(\omega_{\perp}t)$$

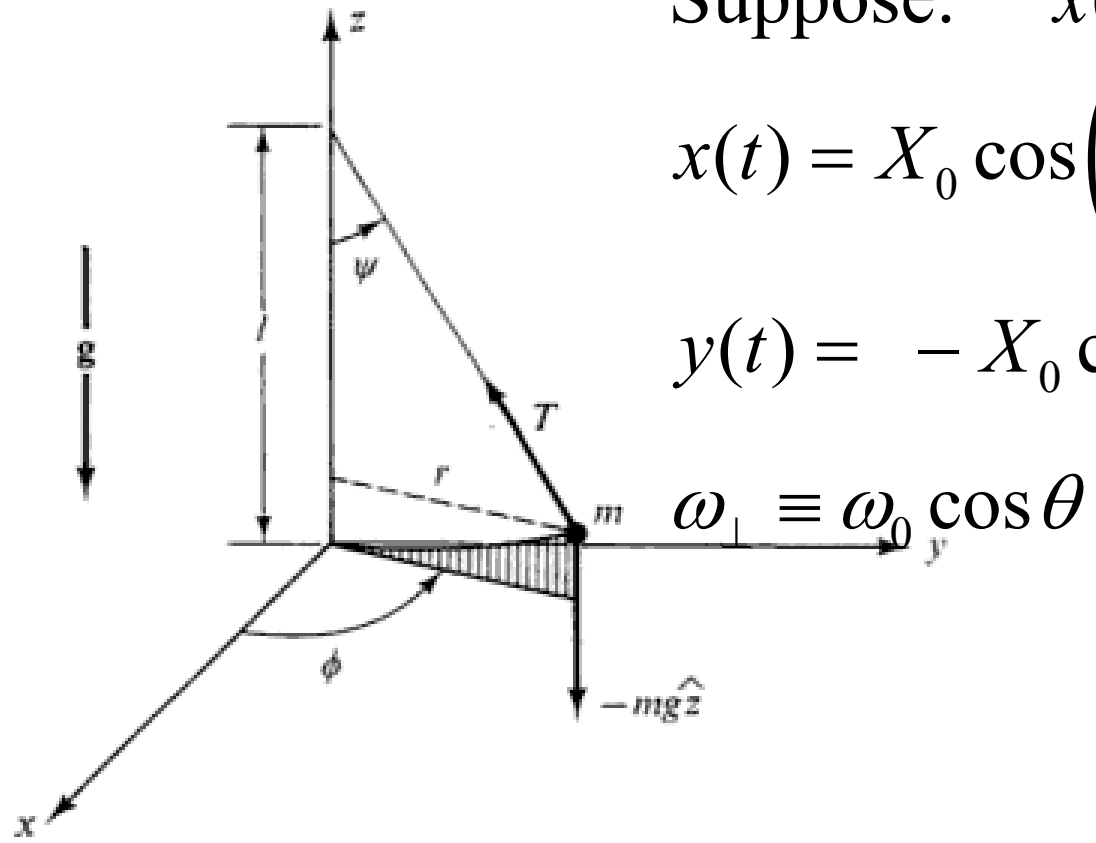


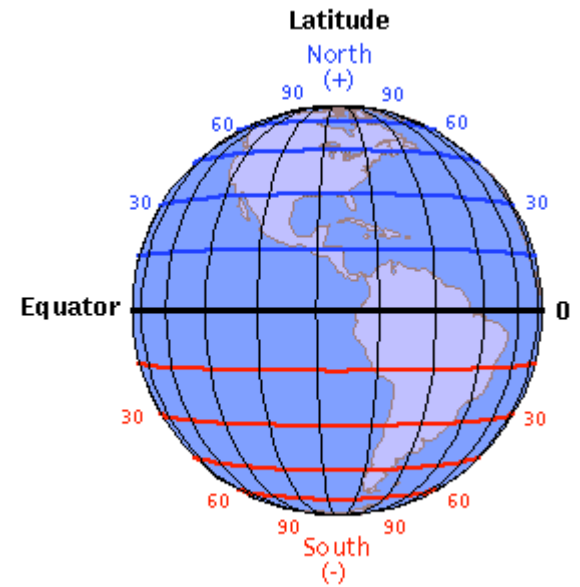
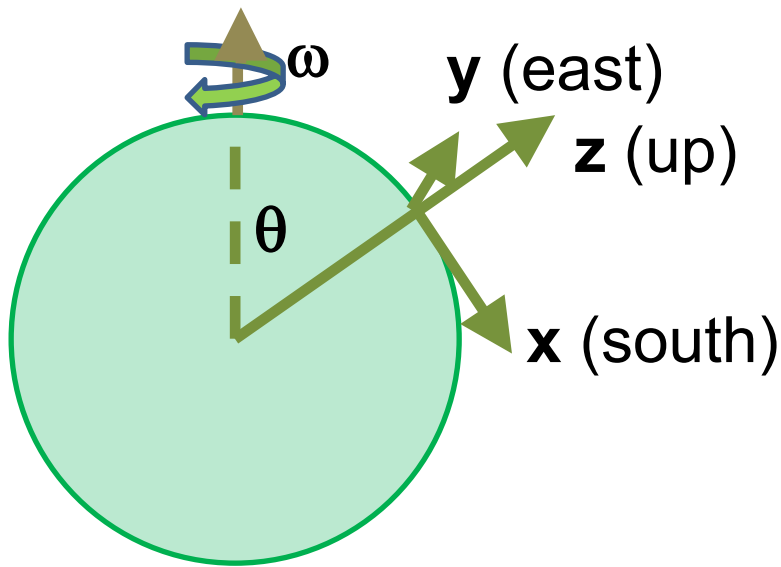
Summary of approximate solution for Foucault pendulum:

Suppose: $x(0) = X_0$ $y(0) = 0$

$$x(t) = X_0 \cos\left(\sqrt{\frac{g}{\ell}}t\right) \cos(\omega_{\perp}t)$$

$$y(t) = -X_0 \cos\left(\sqrt{\frac{g}{\ell}}t\right) \sin(\omega_{\perp}t)$$





Microsoft Illustration

$$\omega_{\perp} \equiv \omega_0 \cos \theta$$

$$x(t) = X_0 \cos\left(\sqrt{\frac{g}{\ell}}t\right) \cos(\omega_{\perp}t)$$

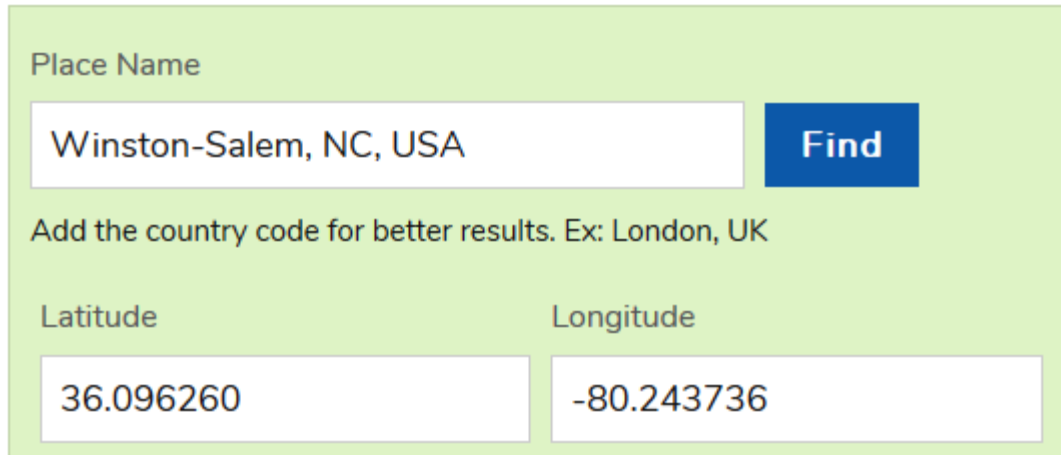
$$y(t) = -X_0 \cos\left(\sqrt{\frac{g}{\ell}}t\right) \sin(\omega_{\perp}t)$$

Latitude and Longitude

<https://www.latlong.net/>

Latitude and Longitude Finder

Latitude and Longitude are the units that represent the *coordinates at geographic coordinate system*. To make a search, use the name of a place, city, state, or address, or click the location on the map to **find lat long coordinates**.



The screenshot shows a web interface for finding coordinates. It features a light green background. At the top, there is a label "Place Name" above a white text input field containing "Winston-Salem, NC, USA". To the right of the input field is a blue button with the word "Find" in white. Below the input field, there is a line of text: "Add the country code for better results. Ex: London, UK". At the bottom, there are two white text input fields. The left one is labeled "Latitude" and contains the value "36.096260". The right one is labeled "Longitude" and contains the value "-80.243736".

Note that $\theta = 90^\circ$ - Latitude