# Notes: Thurs 8/27

1) Elliptic functions
2) Simple pendulum

go beyond small angle approx

## Elliptic Functions:

$$\int \frac{dx}{\sqrt{1-x^2}} = ? = \sin^{-1}(x) + \text{const}$$

$$\sin^{-1}(x) = \arcsin(x)$$

$\rightarrow \sin^2\theta + \cos^2\theta = 1$

subst: $x = \sin\theta \rightarrow \sqrt{1-x^2} = \sqrt{1-\sin^2\theta} = \sqrt{\cos^2\theta} = \cos\theta$

$dx = \cos\theta \, d\theta$

$$\int \frac{\cancel{\cos\theta}\, d\theta}{\cancel{\cos\theta}} = \int d\theta = \theta = \sin^{-1}(x)$$

$x = \sin\theta$

$\theta = \sin^{-1}(x)$

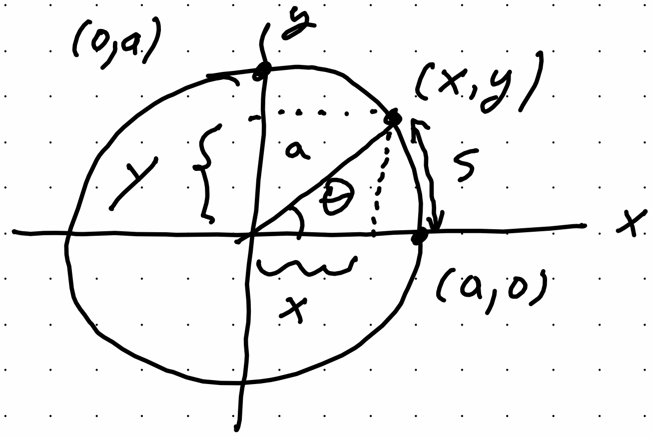
$$\frac{d}{d\theta}\sin\theta = \cos\theta \qquad \lim_{h\to 0}\left(\frac{\sin(\theta+h)-\sin\theta}{h}\right)$$

$$\sin x = x - \frac{1}{3!}x^3 + \frac{1}{5!}x^5 - \cdots$$

$$\sin(A+B) = \sin A\cos B + \cos A \sin B$$

## circular functions..

$x^2+y^2=a^2$ , $a$ = radius



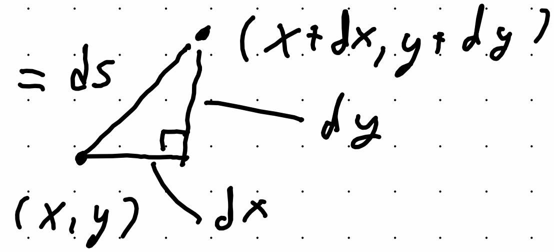

**Def:** $\sin\theta = \dfrac{y}{a}$ , $\cos\theta = \dfrac{x}{a}$

$s$ : arclength from $(a,0)$ to $(x,y)$

$s = a\theta$

$$\theta = \frac{s}{a} = \frac{1}{a}\int ds = \frac{1}{a}\int\sqrt{dx^2+dy^2} = \int d\theta$$

$\sqrt{dx^2+dy^2} = ds$




Given: $x^2+y^2=a^2$

Follows: (i) $\cancel{a^2}\cos^2\theta + \cancel{a^2}\sin^2\theta = \cancel{a^2} \rightarrow \boxed{\cos^2\theta+\sin^2\theta=1}$

(ii) $\boxed{\dfrac{d}{d\theta}\sin\theta} = \dfrac{1}{a}\dfrac{dy}{d\theta} = \dfrac{1}{\cancel{a}}\dfrac{dy}{\frac{1}{\cancel{a}}\sqrt{dx^2+dy^2}} = \dfrac{1}{\sqrt{\left(\frac{dy}{dx}\right)^2+1}}$

$\cancel{2}x\,dx + \cancel{2}y\,dy = 0 \rightarrow dx = -\dfrac{y}{x}dy$

$$= \frac{1}{\sqrt{\frac{x^2+y^2}{x^2}}} = \frac{x}{a} = \boxed{\cos\theta}$$

$$\frac{d(\sin\theta)}{d\theta} = \cos\theta \longrightarrow \int \frac{d(\sin\theta)}{\cos\theta} = \int d\theta$$

$$x = \sin\theta$$

$$\cos\theta = \sqrt{1-\sin^2\theta}$$

$$= \sqrt{1-x^2}$$

$$\boxed{\int \frac{dx}{\sqrt{1-x^2}} = \theta = \sin^{-1}(x)}$$

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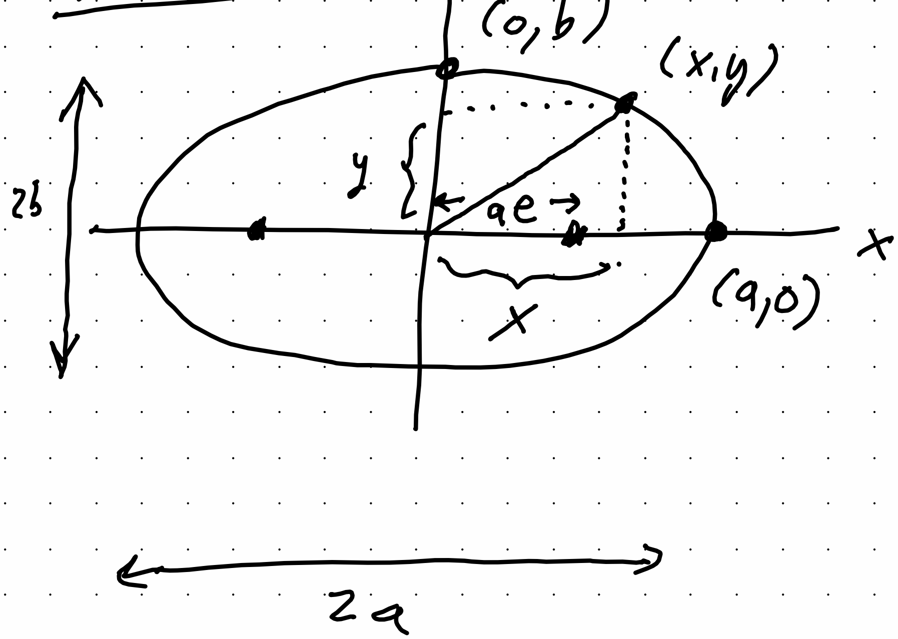
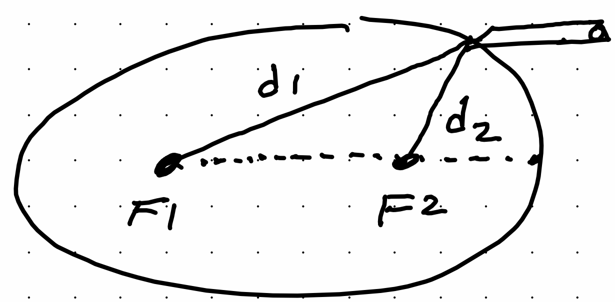
## Elliptic functions

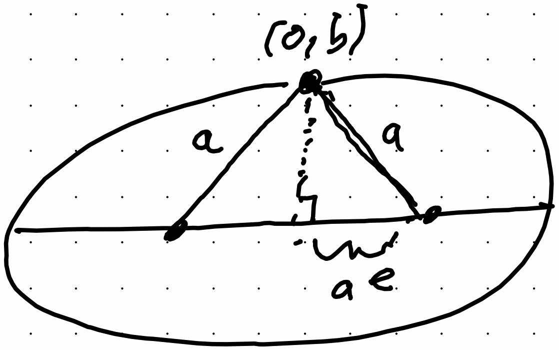



$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1$$

eccentricity : $e = 0$ (for circle)



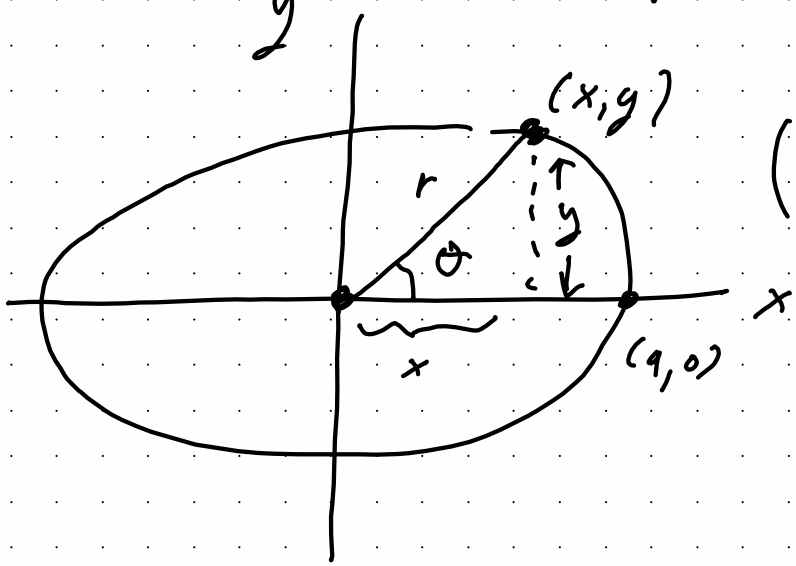

$$d_1 + d_2 = 2a$$




$$(ae)^2 + b^2 = a^2$$
$$a^2e^2 + b^2 = a^2$$
$$e^2 = \frac{a^2-b^2}{a^2} = 1-\left(\frac{b}{a}\right)^2$$

$$\rightarrow \quad e = \sqrt{1-\left(\frac{b}{a}\right)^2} \equiv k$$

notation used in elliptic function




$$\left(\frac{x}{a}\right)^2+\left(\frac{y}{b}\right)^2=1$$

$$x^2+y^2=r^2$$
$$x = r\cos\theta, \quad y = r\sin\theta$$

Define: $\mathrm{cn}(u;k) \equiv \dfrac{x}{a}$, $\quad \mathrm{sn}(u;k) \equiv \dfrac{y}{b}$

$\mathrm{dn}(u;k) \equiv \dfrac{r}{a}$ — (=1 for a circle)

where $u = \dfrac{1}{b}\displaystyle\int_0^\theta r\, d\theta$ $\quad y = r\sin\theta$

(= $\theta$ for a circle)

$$ds = \sqrt{dx^2+dy^2} = \sqrt{dr^2+r^2 d\theta^2}$$

Given: $\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1$ , $x^2 + y^2 = r^2$

$dn(u;k) = \frac{r}{a}$

Follows: (i) $cn^2(u;k) + sn^2(u;k) = 1$

(ii) $dn^2(u;k) + k^2 sn^2(u;k) = 1$

$u = \frac{1}{b}\int_0^\theta r\,d\theta$

(iii) $\frac{d}{du} sn(u;k) = cn(u;k)\,dn(u;k)$

$\frac{d}{du} cn(u;k) = -sn(u;k)\,dn(u;k)$

$\frac{d}{du} dn(u;k) = -k^2 sn(u;k)\,cn(u;k)$

Analogous to

$\frac{d\sin\theta}{d\theta} = \cos\theta$

$\frac{d\sin\theta}{\cos\theta} = d\theta$

$x = \sin\theta$

$\int \frac{dx}{\sqrt{1-x^2}} = \int d\theta = \theta = \sin^{-1}x$

Integrate: $\frac{d\,sn(u;k)}{du} = cn(u;k)\,dn(u;k)$

$\int \frac{d\,sn(u;k)}{cn(u;k)\,dn(u;k)} = \int du = u$

$$\boxed{\int \frac{dx}{\sqrt{1-x^2}\,\sqrt{1-k^2x^2}} = u + \text{const} = sn^{-1}(x;k) + \text{const} \qquad x \equiv sn(u;k)}$$

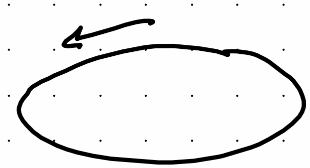
$$\boxed{\int \frac{dx}{\sqrt{1-x^2}} = \sin^{-1}x + \text{const}}$$

$$\int_0^1 \frac{dx}{\sqrt{1-x^2}\sqrt{1-k^2x^2}} \equiv K(k) \longrightarrow$$ related to Period of a pendulum going beyond small-angle approximation

(complete elliptic integral of 1st kind)

$$\int_0^1 \frac{\sqrt{1-k^2x^2}\,dx}{\sqrt{1-x^2}} \equiv E(k) \longrightarrow$$ circumference around an ellipse

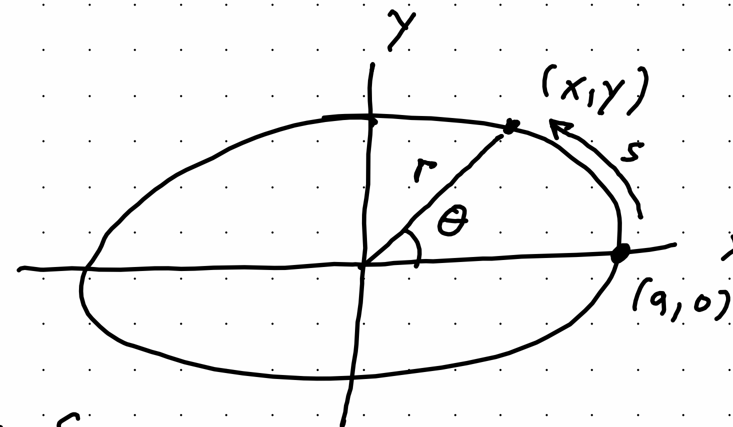
(complete elliptic integral of 2nd kind)



circle: $C = 2\pi a$

Notes: Tuesday 9/1

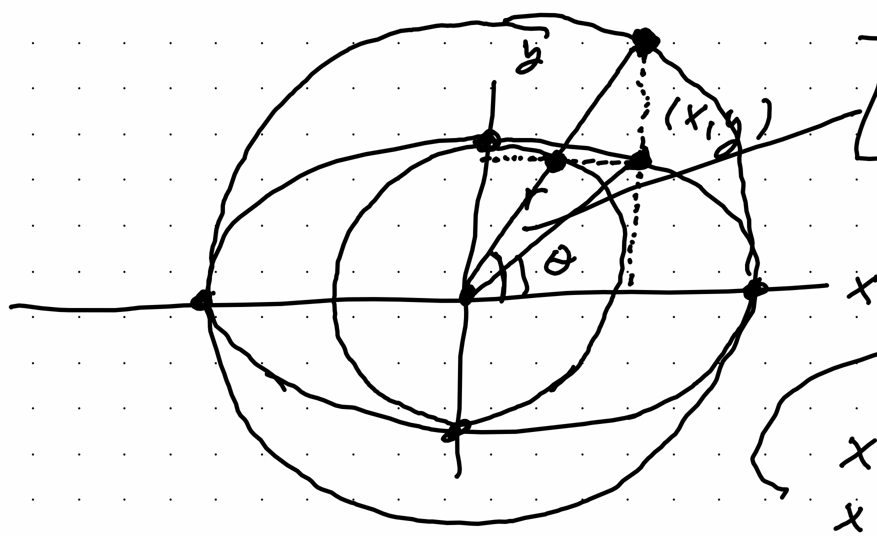
1) Review of elliptic functions
2) Simple pendulum




$$u = \frac{1}{b}\int_{(a,0)}^{(x,y)} r\,d\theta$$

$$bu = \int_0^\theta \underbrace{r\,d\theta} \le \int_0^\theta ds = s$$

$$ds = \sqrt{dx^2 + dy^2} = \sqrt{\underbrace{dr^2} + r^2 d\theta^2} \ge r\,d\theta$$

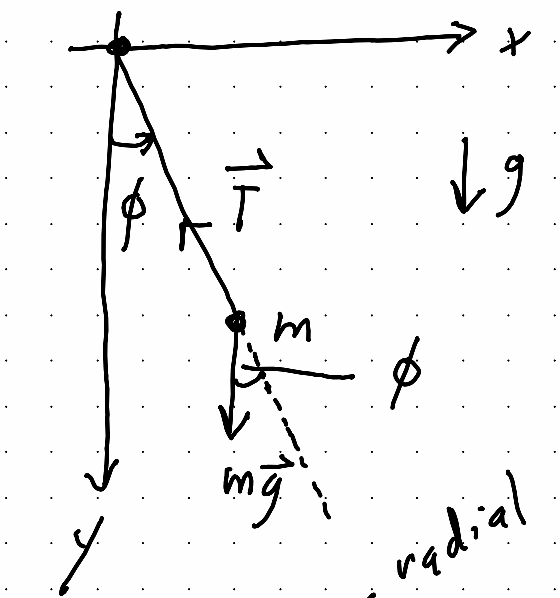


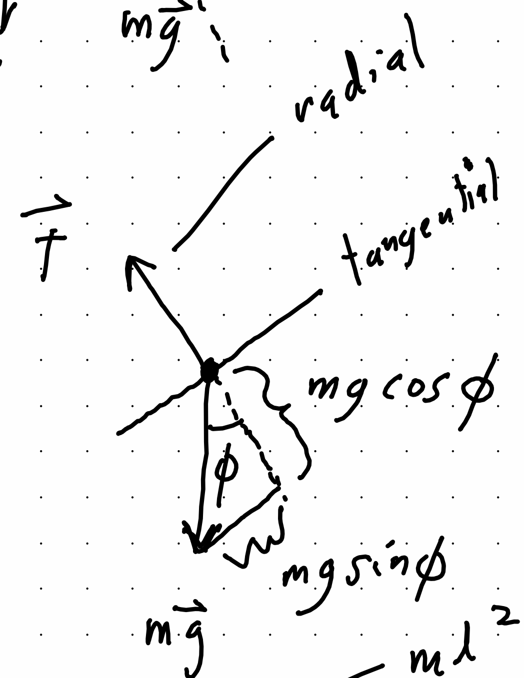

$\boxed{\phi}$

$x = r\cos\theta$
$y = r\sin\theta$
$x = a\cos\phi$
$y = b\sin\phi$

$x = a\cos\phi\,,\quad y = \underline{\underline{a}}\sin\phi$
$x = b\cos\phi \quad y = b\sin\phi$

## Simple pendulum:




$$\text{Torque} = \overset{ml^2}{I}\,\overset{\ddot\phi}{\alpha}$$

(i) "Freshman physics"

forces, free-body diagram

$\longrightarrow$ EOM, tension

**tangential:**

$$-mg\sin\phi = m\,a_{tangential}$$

$$-\cancel{m}g\sin\phi = \cancel{m}l\ddot\phi$$

$\phi$ : angular displacement [rad]

$\dot\phi$ : angular velocity [rad/sec]

$\ddot\phi$ : angular accel [rad/sec$^2$]

$$\boxed{\ddot\phi = -\frac{g}{l}\sin\phi} \quad \text{(EOM)}$$

**radial:** $T - mg\cos\phi = m\,a_{centripetal}$

$$T - mg\cos\phi = m\dot\phi^2 l$$

$$T = mg\cos\phi + m\dot\phi^2 l$$

(ii) Small angle approximation:

$$\sin\phi \approx \phi \longleftarrow \underbrace{\phi \ll 1}_{\text{radian}} = 57 \text{ degrees}$$

$$\ddot{\phi} = -\frac{g}{l}\sin\phi \approx -\frac{g}{l}\phi \rightarrow \boxed{\ddot{\phi} = -\frac{g}{l}\phi}$$

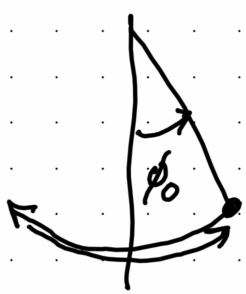
small angle approx.

$$\phi(t) = \boxed{a}\cos(\omega t) + \boxed{b}\sin(\omega t)$$

determined by initial conditions

where $\omega \equiv \sqrt{\frac{g}{l}}$

<u>ICs:</u> If $\phi(0) = \phi_0$ (at rest)




then $\boxed{\phi(t) = \phi_0 \cos(\omega t)}$

<u>Period:</u> $P = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{l}{g}}$

independent of $\phi_0$ !!

(iii) Lagrangian approach

$T \equiv$ Kinetic energy

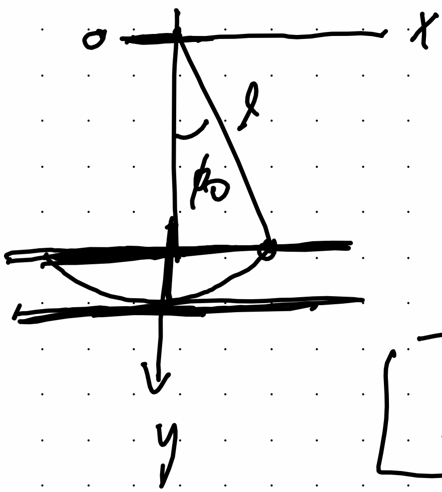
$U \equiv$ Potential energy

$$L = T - U$$

$$\boxed{T = \frac{1}{2} m l^2 \dot{\phi}^2} \quad \left( = \frac{1}{2} m (\dot{x}^2 + \dot{y}^2) \right)$$

$y = l \cos\phi$

$x = l \sin\phi$




$$\boxed{U = -mgl\cos\phi + \text{const}} \leftarrow U = -mgy$$

$$U = mgl(1-\cos\phi)$$

$$\boxed{L = \frac{1}{2} m l^2 \dot{\phi}^2 + mgl\cos\phi}$$

action

$$\boxed{S = \int_{t_1}^{t_2} dt\, L(\phi, \dot{\phi}, t)}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right) = \frac{\partial L}{\partial \phi}$$

Lagrange's equation

$$\frac{d}{dt}\left(m l^2 \dot{\phi}\right) = -mgl\sin\phi$$

$$m l^2 \ddot{\phi} = -mgl\sin\phi \rightarrow \boxed{\ddot{\phi} = -\frac{g}{l}\sin\phi} \quad (\text{EOM})$$

(iv) solving $\ddot{\phi} = -\frac{g}{l}\sin\phi$ (2nd order non-linear ODE) ← hard!!

$$E = \text{const}$$
$$= T + U$$
$$= \frac{1}{2}ml^2\dot{\phi}^2 - mgl\cos\phi$$

$$E = 0 - mgl\cos\phi_0$$
$$= -mgl\cos\phi_0$$

release from rest from $\phi = \phi_0$

$$-mgl\cos\phi_0 = \frac{1}{2}ml^2\dot{\phi}^2 - mgl\cos\phi$$

$$-\cancel{m}gl(\cos\phi_0 - \cos\phi) = \frac{1}{2}\cancel{m}l^2\dot{\phi}^2$$

$$\frac{d\phi}{dt} = \dot{\phi} = \sqrt{-2\frac{g}{l}(\cos\phi_0 - \cos\phi)}$$

$|\phi| \leq \phi_0$

separable 1st order ODE

$$\int \frac{d\phi}{\sqrt{-\frac{2g}{l}(\cos\phi_0 - \cos\phi)}} = \int dt = t + \text{const}$$

$$t + t_0 = \int \frac{d\phi}{\sqrt{-2\frac{g}{l}\left(\cos\phi_0 - \cos\phi\right)}}$$

$$\frac{1}{\sqrt{a + bx^2}}$$

substitution:

$$\cos\phi = 1 - 2\sin^2\left(\frac{\phi}{2}\right)$$

$$\cos\phi_0 = 1 - 2\sin^2\left(\frac{\phi_0}{2}\right)$$

$$\cos\phi = \cos\left(2\left(\frac{\phi}{2}\right)\right)$$

$$= \cos^2\left(\frac{\phi}{2}\right) - \sin^2\left(\frac{\phi}{2}\right)$$

$$= 1 - 2\sin^2\left(\frac{\phi}{2}\right)$$

$$\rightarrow \cos\phi_0 - \cos\phi = -2\left(\sin^2\left(\frac{\phi_0}{2}\right) - \sin^2\left(\frac{\phi}{2}\right)\right)$$

$$t + t_0 = \int \frac{d\phi}{2\sqrt{\frac{g}{l}}\sqrt{\sin^2\left(\frac{\phi_0}{2}\right) - \sin^2\left(\frac{\phi}{2}\right)}}$$

$$|\phi| \leq \phi_0$$

$$= \frac{1}{2\sqrt{\frac{g}{l}}} \int \frac{d\phi}{\sin\left(\frac{\phi_0}{2}\right)\sqrt{1 - \frac{\sin^2\left(\frac{\phi}{2}\right)}{\sin^2\left(\frac{\phi_0}{2}\right)}}}$$

let $x = \frac{\sin(\phi/2)}{\sin\left(\frac{\phi_0}{2}\right)}$

$$\boxed{x = \frac{\sin\left(\frac{\phi}{2}\right)}{\sin\left(\frac{\phi_0}{2}\right)}} \longrightarrow dx = \frac{1}{\sin\left(\frac{\phi_0}{2}\right)} \frac{1}{2} \cos\left(\frac{\phi}{2}\right) d\phi$$

$\sqrt{1-x^2}$

denominator

$$d\phi = \frac{2\sin\left(\frac{\phi_0}{2}\right) dx}{\cos\left(\frac{\phi}{2}\right)}$$

$$= \frac{2\sin\left(\frac{\phi_0}{2}\right) dx}{\sqrt{1-\sin^2\left(\frac{\phi}{2}\right)}}$$

$$= \frac{2\sin\left(\frac{\phi_0}{2}\right) dx}{\sqrt{1-\underbrace{\sin^2\left(\frac{\phi_0}{2}\right)}_{k^2} x^2}}$$

Find this out

1. $\phi(t) = \cancel{\boxed{\phantom{xx}}}$
2. Period = ??
3. Redo the analysis using Lagrange multiplier for find tension in string

$t + t_0 = \int \bigcirc$ — integrand for $sn^{-1}(x; k)$

$k = \sin\left(\frac{\phi_0}{2}\right)$

## Lec #4 : Thurs 9/3

$$\phi(t) = 2\sin^{-1}\left[k\,\mathrm{sn}\left(\omega_0\left(t+\frac{P}{4}\right);k\right)\right]$$

$$k \equiv \sin\left(\frac{\phi_0}{2}\right), \quad \omega_0 = \sqrt{\frac{g}{\ell}}$$

$$P = 4\sqrt{\frac{\ell}{g}}\,K(k) = 4\sqrt{\frac{\ell}{g}}\int_0^1 \frac{dx}{\sqrt{1-x^2}\,\sqrt{1-k^2x^2}}$$

small angle approx

$$P_0 = 2\pi\sqrt{\frac{\ell}{g}}$$

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$$\frac{\sin\left(\frac{\phi}{2}\right)}{\sin\left(\frac{\phi_0}{2}\right)} = x = \mathrm{sn}\left[\sqrt{\frac{g}{\ell}}(t+t_0);k\right]$$

$$\sqrt{\frac{\ell}{g}}\int\frac{dx}{\sqrt{1-x^2}\,\sqrt{1-k^2x^2}} = \sqrt{\frac{\ell}{g}}\,\mathrm{sn}^{-1}(x;k) = t+t_0$$

$$\mathrm{sn}^{-1}(x;k) = \sqrt{\frac{g}{\ell}}(t+t_0)$$

$$P = 4\sqrt{\frac{l}{g}}\,K(k) = \underbrace{2\pi\sqrt{\frac{l}{g}}\left(1 + \frac{1}{16}\phi_0^2 + \dots\right)}_{\text{problem Landau 11,1}}$$

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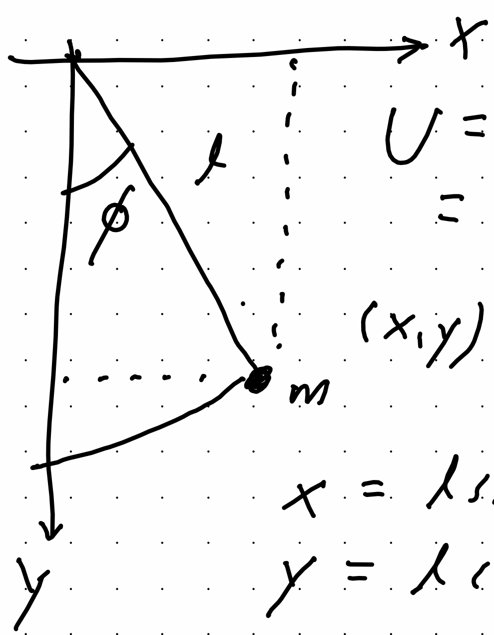
Lagrange multiplier:




$$U = -mgy$$
$$= -mgl\cos\phi$$

$$x = l\sin\phi$$
$$y = l\cos\phi$$

$$\underbrace{\phi(x,y)}_{\text{constraint function}} = x^2 + y^2 - l^2 = 0$$

$$x^2 + y^2 = l^2\sin^2\phi + l^2\cos^2\phi$$
$$= l^2$$

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$$T = \frac{1}{2}m(\dot{x}^2 + \dot{y}^2)$$
$$= \frac{1}{2}ml^2\dot{\phi}^2$$

$$L = T - U + \lambda \varphi$$

Lagrange multiplier

$\lambda, \cancel{\dot{x}}$

$L(x, \dot{x}, y, \dot{y}, t) \quad q = (x, y) \quad \dot{q} = (\dot{x}, \dot{y})$

$L(r, \dot{r}, \phi, \dot{\phi}, t) \quad q = (r, \phi) \quad \dot{q} = (\dot{r}, \dot{\phi})$

$\lambda(t)$
$r(t)$
$\phi(t)$

$L(\phi, \dot{\phi}, t) \quad \varphi(x, y) = x^2 + y^2 - l^2 = 0 \quad \boxed{\varphi(r, \phi) = r - l = 0}$

$$\boxed{L = \frac{1}{2} m (\dot{r}^2 + \underline{r^2 \dot{\phi}^2}) + mg \underbrace{r\cos\phi}_{y} + \lambda (r - l)}$$

$\underline{r}$: $\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{r}}\right) = \frac{\partial L}{\partial r} \rightarrow \boxed{\cancel{m\ddot{r}} = mr\dot{\phi}^2 + mg\cos\phi + \lambda}$

$\underline{\phi}$: $\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right) = \frac{\partial L}{\partial \phi} \rightarrow \frac{d}{dt}(mr^2\dot{\phi}) = -mgr\sin\phi$

$\underline{\lambda}$: $r - l = 0$ ✓ $\quad \cancel{2mr\dot{r}\dot{\phi}} + mr^2\ddot{\phi} = -mgr\sin\phi$

$$r - l = 0 \longrightarrow r = l$$

$$\dot{r} = 0$$

$$\ddot{r} = 0$$

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$$\longrightarrow \quad \ddot{\phi} = -\frac{g}{l} \sin\dot{\phi}$$

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$$ml\dot{\phi}^2 + mg\cos\phi + \lambda = 0$$

$$\boxed{\lambda = -\underbrace{\left(mg\cos\phi + ml\dot{\phi}^2\right)}_{T}}$$

$$\lambda = -T$$

$$L = T - U + \lambda \varphi$$

$U = U(x, t)$

$T = \frac{1}{2} m (\dot{x}^2 + \dot{y}^2)$

$\varphi(x, y, t)$

$U(x, y, t)$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = \frac{\partial L}{\partial x}$$

$$\frac{d}{dt}(m\dot{x}) = -\frac{\partial U}{\partial x} + \lambda \frac{\partial \varphi}{\partial x}$$

$$\frac{d}{dt}(m\dot{y}) = -\frac{\partial U}{\partial y} + \lambda \frac{\partial \varphi}{\partial y}$$

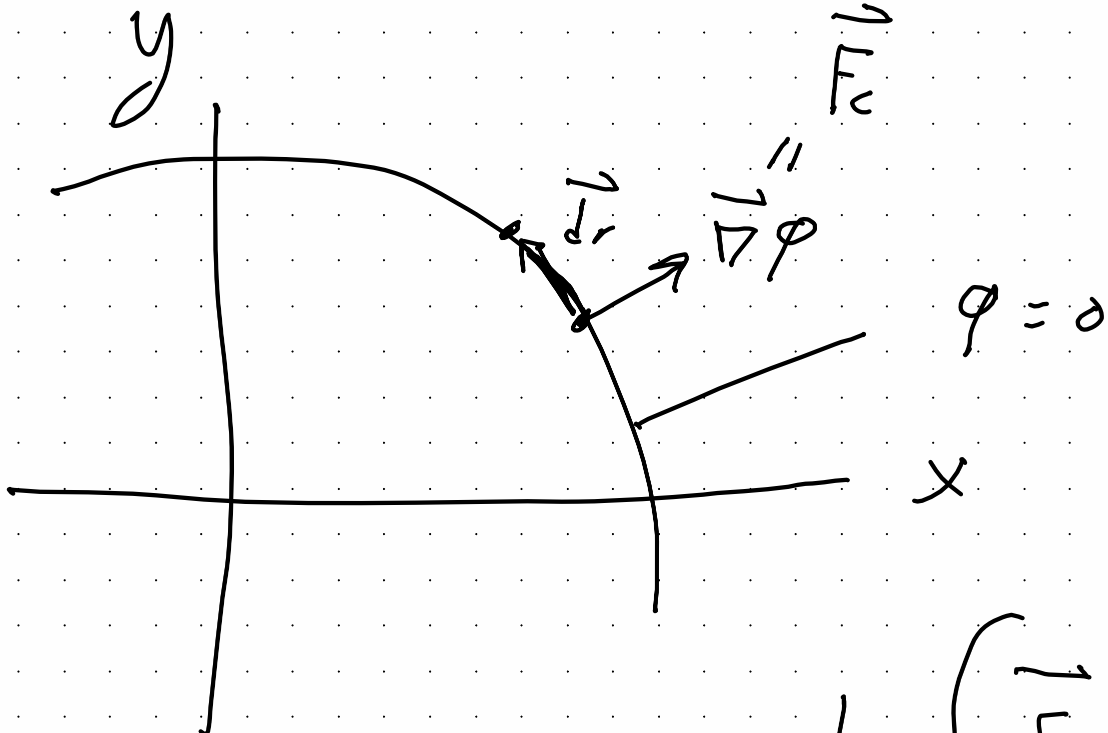
$$\boxed{\frac{d\vec{p}}{dt} = \vec{F}_{net}}$$

applied force

force constraint

$$\left.\begin{aligned} \frac{dp_x}{dt} &= F_x + \lambda \frac{\partial \varphi}{\partial x} \\ \frac{dp_y}{dt} &= F_y + \lambda \frac{\partial \varphi}{\partial y} \end{aligned}\right\} \quad \boxed{\frac{d\vec{p}}{dt} = \vec{F} + \lambda \vec{\nabla}\varphi}$$

$$\left(\frac{\partial \varphi}{\partial x}, \frac{\partial \varphi}{\partial y}\right) = \vec{\nabla}\varphi$$



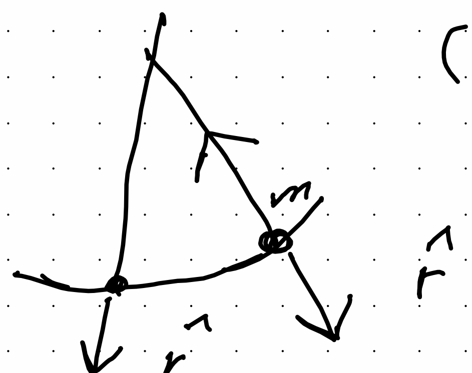

$$\int \underbrace{\vec{F}_c \cdot d\vec{r}}_{0} = \text{Work}$$

$$\vec{\nabla}\varphi \perp \varphi = \text{const}$$

$$\varphi = r - \ell$$

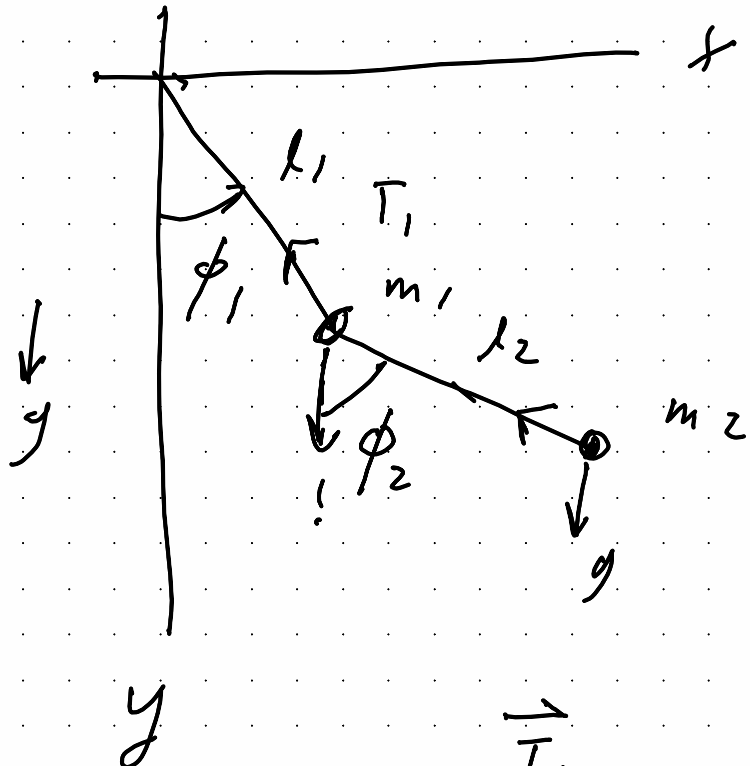
$$\vec{\nabla}\varphi = \hat{r}$$

$$\lambda \vec{\nabla}\varphi$$




$(r, \phi)$

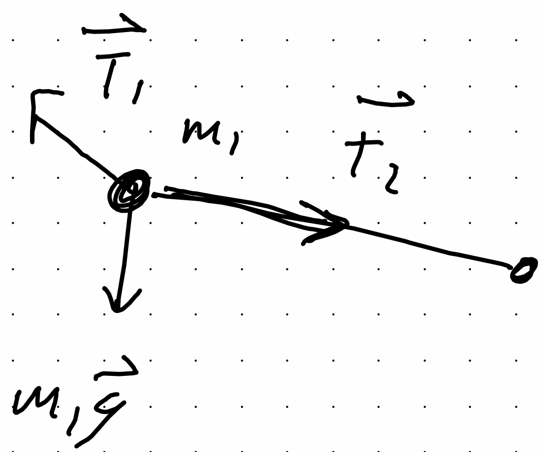
$\hat{r}, \hat{\phi}$




$$U = -m_1 g y_1 - m_2 g y_2$$

$\ddot{\phi}_1$ , $\ddot{\phi}_2$

EOM



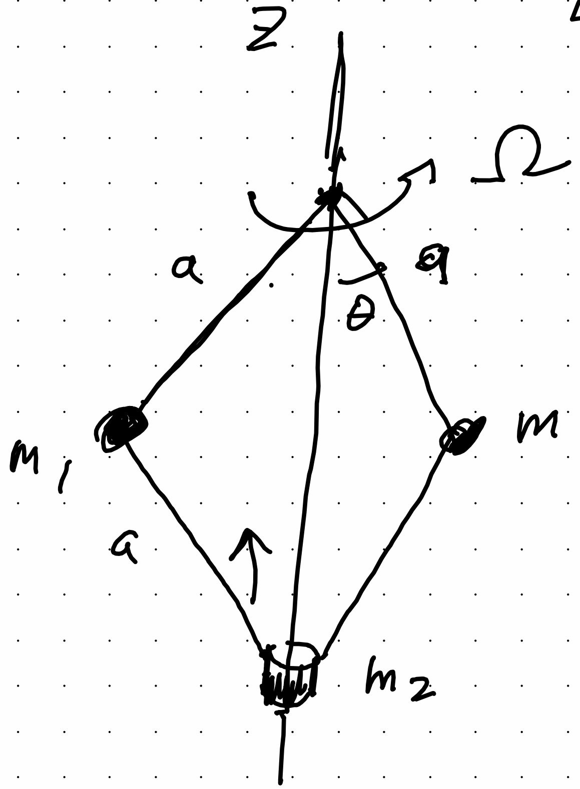

$\lambda\varphi$

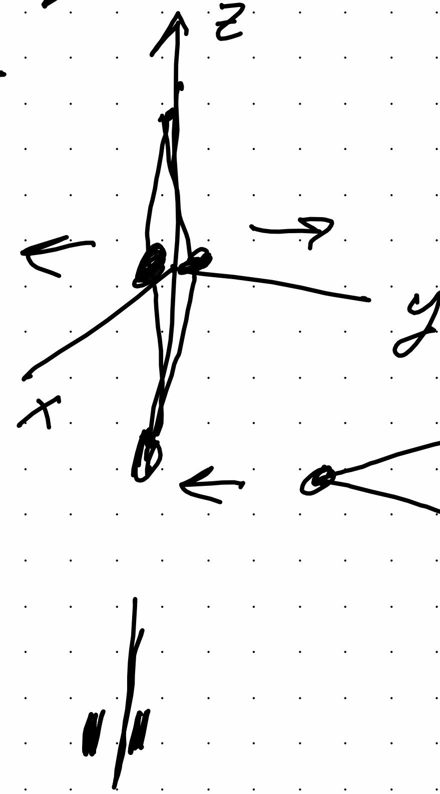
$(l_1\varphi_1 + l_2\varphi_2$
$+ \dots)$

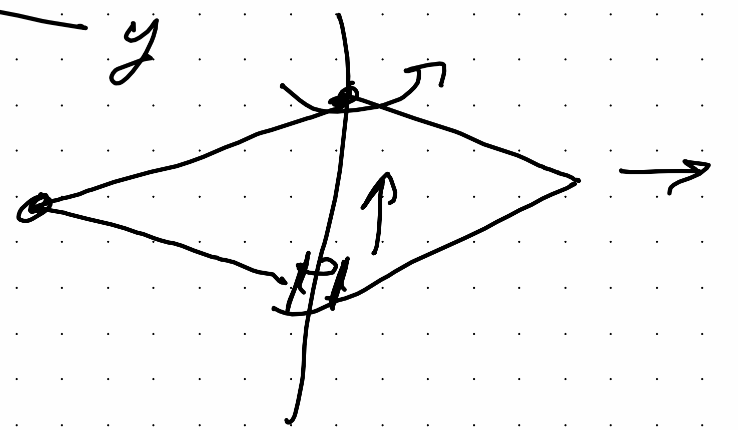
$$L \longrightarrow \text{EoM}$$

$$L \longrightarrow \underbrace{L + \frac{d}{dt}\left(f(q,t)\right)}_{L'}$$

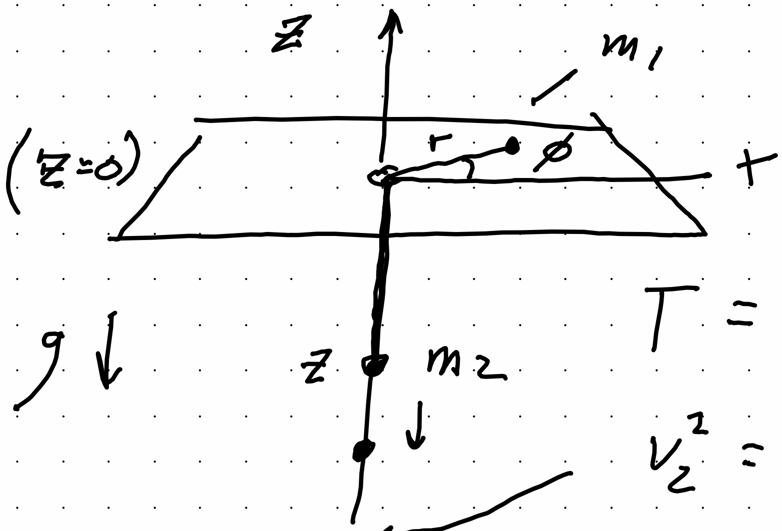
$$f(q, \cancel{\dot{q}}, t)$$



Lec #5: Tuesday 9/18




$$\boxed{r - z = l} = \text{length of string}$$

$$L = T - U$$

$$T = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2$$

$$v_2^2 = \dot{z}^2, \quad v_1^2 = \dot{r}^2 + r^2\dot{\phi}^2$$

$$\left(= \dot{x}^2 + \dot{y}^2, \quad \begin{matrix} x = r\cos\phi \\ y = r\sin\phi \end{matrix}\right)$$

$$v_2^2 = \dot{r}^2$$

$$T = \frac{1}{2} m_1 (\dot{r}^2 + r^2\dot{\phi}^2) + \frac{1}{2} m_2 \dot{r}^2$$

$$\boxed{T = \frac{1}{2}(m_1 + m_2)\dot{r}^2 + \frac{1}{2} m_1 r^2 \dot{\phi}^2}$$

$$U = m_2 g z = m_2 g (r - l) = \underline{m_2 g r} - \underbrace{m_2 g l}_{\text{constant}}$$

$$\boxed{U = m_2 g r}$$

$$L = T - U = \boxed{\frac{1}{2}(m_1 + m_2)\dot{r}^2 + \frac{1}{2} m_1 r^2 \dot{\phi}^2 - m_2 g r}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot r}\right) = \frac{\partial L}{\partial r}, \quad \frac{d}{dt}\left(\frac{\partial L}{\partial \dot\phi}\right) = \frac{\partial L}{\partial \phi} \implies 2^{nd} \text{ order EOMs}$$

<u>No explicit $t$ dependence:</u>

$$E = \dot r \frac{\partial L}{\partial \dot r} + \dot\phi \frac{\partial L}{\partial \dot\phi} - L = \boxed{T+U}$$

$$E = \sum_i \dot q_i \underbrace{\frac{\partial L}{\partial \dot q_i}}_{= p_i} - L$$

<u>No explicit $\phi$ dependence:</u>

$$p_\phi \equiv \frac{\partial L}{\partial \dot\phi} = \text{const} = M_z$$

$\vec{M}$: angular momentum (L&L notation)

$$\boxed{M_z = m_1 r^2 \dot\phi} \rightarrow \boxed{\dot\phi = \frac{M_z}{m_1 r^2}}$$

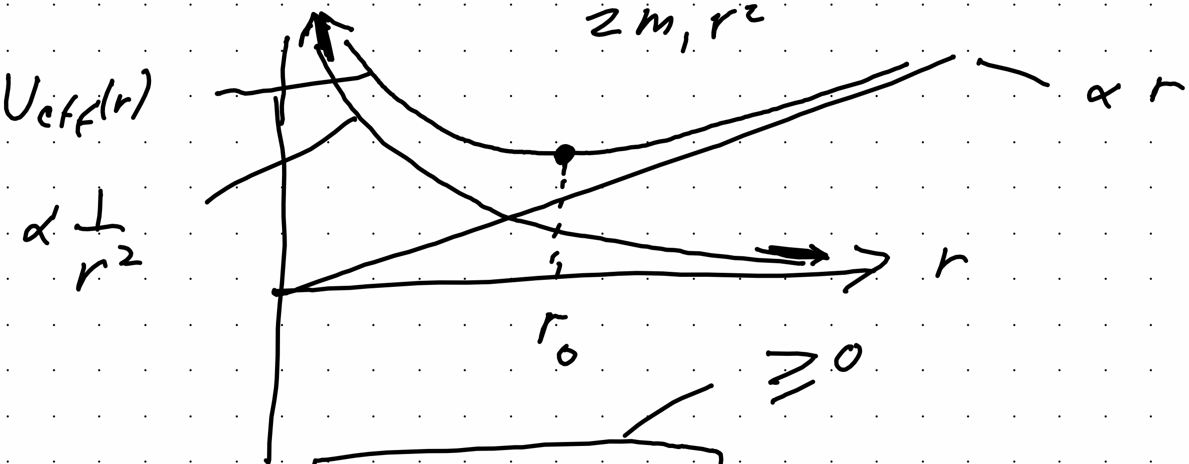
$$E = \tfrac{1}{2} m \dot x^2 + U(x)$$

$$\boxed{E = \tfrac{1}{2}(m_1+m_2)\dot r^2 + \tfrac{1}{2} m_1 r^2 \dot\phi^2 + m_2 g r}$$

$$\boxed{E = \tfrac{1}{2}(m_1+m_2)\dot r^2 + \left(\frac{M_z^2}{2 m_1 r^2} + m_2 g r\right)} \leftarrow \boxed{U_{eff}(r) = U(r) + \frac{M_z^2}{2 m_1 r^2}}$$

$$U_{eff}(r) = \frac{M_z^2}{2m_1 r^2} + m_2 g r$$

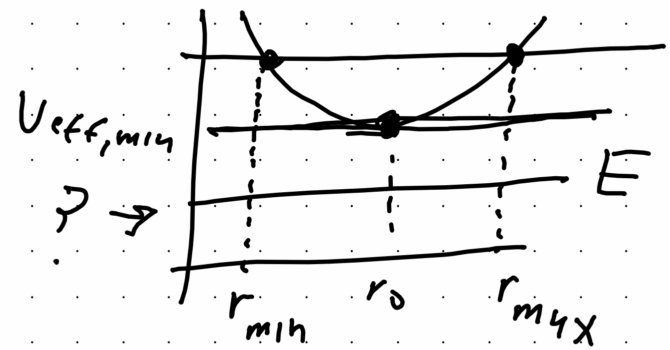
$\left( U(r) = m_2 g r \right.$




$r_{min}, r_{max}$: "turning points" ($\dot r = 0$)

$$E = \underbrace{\boxed{\frac{1}{2}(m_1+m_2)\dot r^2}}_{\geq 0} + U_{eff}(r)$$

const




i) $E = U_{eff,min} = U_{eff}(r_0)$

unif circular motion: $r = r_0$, $\dot\phi = \frac{M_z}{m_1 r_0^2}$

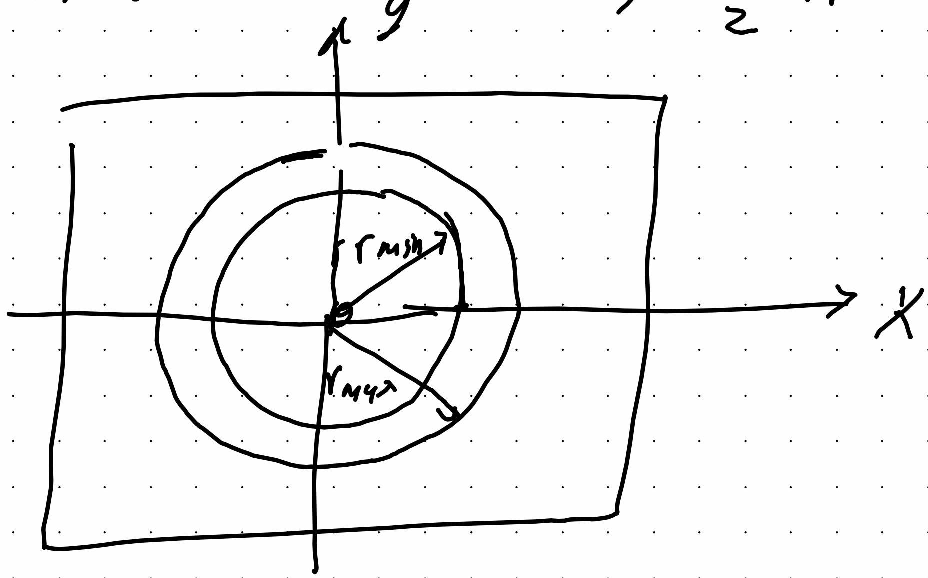
$E < U_{eff,min}$ (not allowed)

ii) $E > U_{eff,min}$

$E = U_{eff}(r_{min}) = U_{eff}(r_{max})$

$E \geq U_{eff,min}$

top view



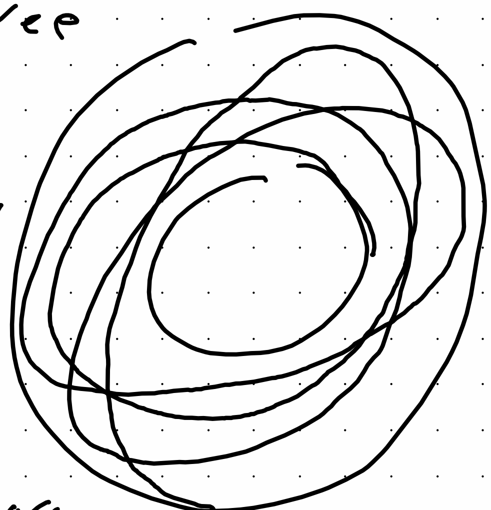

$U(r) = \frac{1}{2} k r^2$ — closed bound orbits

$$\underbrace{U(r) = -\frac{G m_1 m_2}{r}}_{\text{Newtonian gravity}}$$

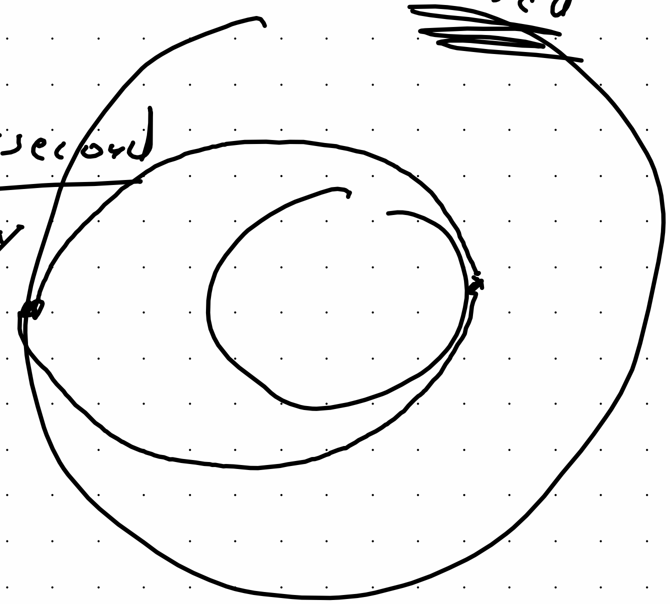
bound orbits are closed = ellipse

1 degree
=
60 mins of arc

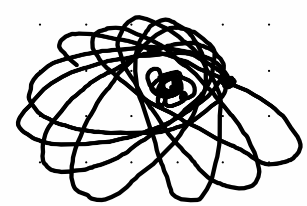
1 min of arc
=
60 sec of arc



$\frac{43 \text{ arcsecond}}{\text{century}}$



perihelion precession of Mercury
— closest approach to sun



$\underline{r_0}$ : $\left.\dfrac{dU_{eff}}{dr}\right|_{r=r_0} = 0$ (minimum)

$$0 = \frac{d}{dr}\left(\frac{M_z^2}{2m_1r^2} + m_2gr\right)\Big|_{r=r_0}$$

$$= -\frac{M_z^2}{m_1r_0^3} + m_2g$$

$$\boxed{M_z^2 = m_1m_2gr_0^3}$$

tells you the value of $M_z$ needed to have a specific $r_0$ value.

For a given $M_z$, this tells you what $r_0$ equals.

## Energy equation:

$$E = \frac{1}{2}(m_1 + m_2)\dot{r}^2 + \frac{M_z^2}{2m_1 r^2} + m_2 g r$$

$$\boxed{\dot{\phi} = \frac{M_z}{m_1 r^2}} \leftarrow \phi \text{ equation}$$

$$\frac{1}{2}(m_1 + m_2)\dot{r}^2 = E - \frac{M_z^2}{2m_1 r^2} - m_2 g r$$

$$\dot{r} = \frac{dr}{dt} = \pm\sqrt{\left(\frac{2}{m_1 + m_2}\right)\left(E - \frac{M_z^2}{2m_1 r^2} - m_2 g r\right)}$$

$$\int \frac{dr}{\pm\sqrt{\left(\frac{2}{m_1 + m_2}\right)\left(E - \frac{M_z^2}{2m_1 r^2} - m_2 g r\right)}} = \int dt = t + \text{const}$$

$$t(r) \longleftrightarrow r(t)$$

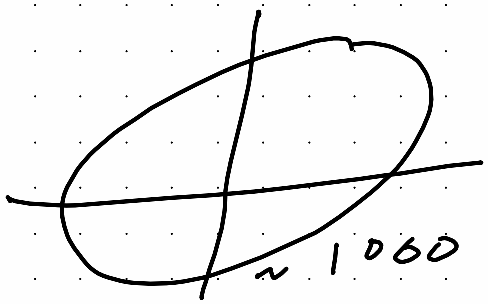
orbital equation:     $r = r(\phi) \quad \Longleftrightarrow \quad \phi = \phi(r)$

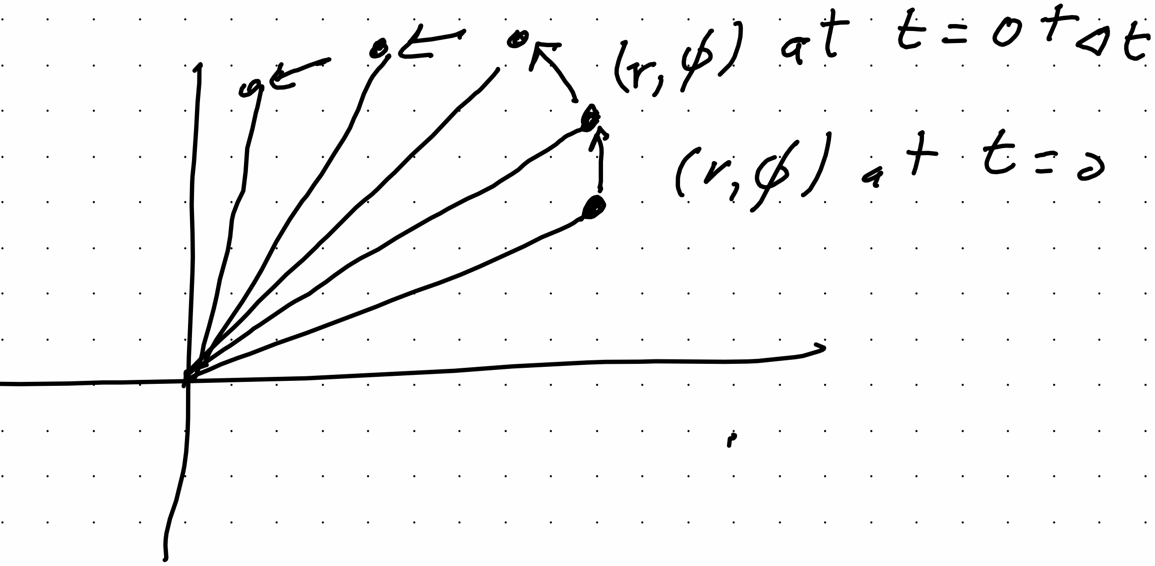
$$\frac{dr}{dt} = \dot{r} = \sqrt{\left(\frac{2}{m_1+m_2}\right)\left[E - \frac{M_z^2}{2m_1r^2} - m_2 g r\right]}$$

$$\frac{dr}{dt} = \underbrace{\frac{dr}{d\phi}}_{\mathrm{hi}}\frac{d\phi}{dt} = \frac{dr}{d\phi}\frac{M_z}{m_1r^2}$$

$$\rightarrow \quad \frac{dr}{d\phi} = \frac{m_1r^2}{M_z}\sqrt{\left(\frac{2}{m_1+m_2}\right)\left[\qquad\right]}$$

$$\int \frac{dr}{\frac{m_1r^2}{M_z}\sqrt{(\;)[\qquad]}} = \int d\phi = \phi + \text{const}$$




Know: $r, \phi$ at some time $t$

given: $\Delta t$ need to know $\Delta r$ and $\Delta \phi$

$$r(t+\Delta t) = r(t) + \Delta r(t) + \ldots$$

$$\phi(t+\Delta t) = \phi(t) + \Delta \phi(t) + \underbrace{\ldots}_{\text{ignore if } \Delta t \text{ is suff. small}}$$