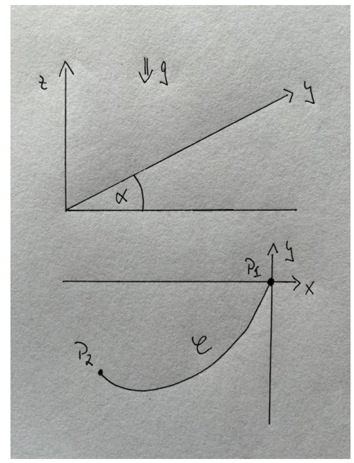
PHYS 622 | Classical Electrodynamics | W 2024

Problem Assignment # 1 | 01/10/2024
due 01/17/2024

0.2.1 **The brachistochrone problem**

A point mass glides without friction on an inclined plane (inclination angle α) from point P_1 to point P_2 on a path $\mathfrak{C}$ according to Galilean mechanics.



a) Use energy conservation to find the velocity as a function of y, using the coordinate system in the sketch.

b) Write the passage time from P_1 to P_2 in the form

$$T = \int_{x_1}^{x_2} dx\, L(y, y')$$

with y considered a function of x and $y' = dy/dx$, and determine the Lagrangian L. Use the fact that Jacobi's integral is constant to find an ODE for y.

c) Substitute $y' = \cot t$ to write the brachistochrone, i.e., the solution of the ODE from part b), in a parametric form, $y = y(t)$, $x = x(t)$.

d) Express the passage time as a function of the value t_2 of the brachistochrone parameter in the point P_2 (or, equivalently, as a function of $y_2' = (dy/dx)_{\mathrm{P}_2}$, which has a more intuitive meaning).

e) Find the passage time for the shortest path from P_1 to P_2 (as opposed to the brachistochrone) as a function of t_2.

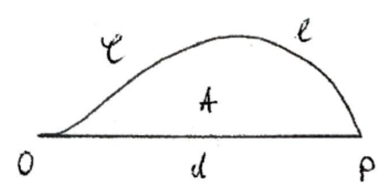
f) Discuss the ratio of the two passage times as a function of t_2.

hint: The parameter value t_2 for the brachistochrone at the end point P_2 is a known function of y_2'. It therefore suffices to discuss the passage time as a function of t_2.

(18 points)

0.2.2 **Dido's problem**

An area A in the x-y-plane is enclosed by a straight line between two points O and P that are a distance d apart, and a path $\mathfrak{C}$ with end points O and P and length $\ell > d$. Find the path $\mathfrak{C}$ that maximizes A.



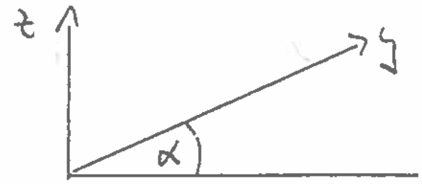
(6 points)

0.2.3 **Geodesics on the 2-sphere**

Show that the geodesics on the 2-sphere are great circles.

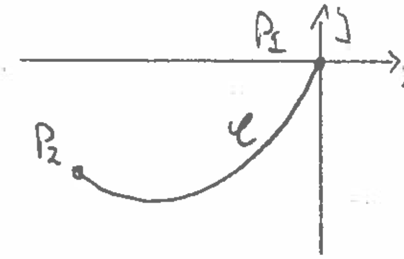
hint: There are various ways of doing this. One is to set up the problem of geodesics in $\mathbb{R}_3$ with the constraint that the desired paths $\vec{x}(t)$ must lie on the sphere. Now use the Euler-Lagrange equations for the constrained problem to show that $\vec{\ell} = \vec{x} \times \vec{p} = \text{const}$, where $\vec{p} = \partial L/\partial\dot{\vec{x}}$, with L the appropriate Lagrangian.

(5 points)



0.2.1.) constraint: $z = y \sin\alpha$

let $P_1 = (0,0,0)$ wlog



a) Energy conservation →

$$\frac{m}{2}v^2 = -mgz = -mgy\sin\alpha$$

(1) → $\underline{v(x,y)} = v(y) = \sqrt{2g\sin\alpha}\sqrt{-y} =: \underline{\sqrt{-ay}}$ where $\underline{a := 2g\sin\alpha}$

b) length of infinitesimal path segment: $dl = dt\sqrt{\dot x^2+\dot y^2}$

(1) Time needed to move across dl : $dT = dl/v(y)$

→ Passage time

$$T = \int_{t_1}^{t_2} dt \, \frac{1}{v(y)}\sqrt{\dot x^2+\dot y^2} = \int_{x_1}^{x_2} dx \, \frac{1}{v(y)}\sqrt{1+y'^2}$$

(1) $$= \int_{x_1}^{x_2} dx \, L(y,y') \quad \text{with} \quad L(y,y') = \frac{1}{v(y)}\sqrt{1+y'^2}$$

cf. §2.3 remark (3)(ii) → Jacobi's integral is a constant of motion, i.e.,

$$H(y,y') = y'\frac{\partial L}{\partial y'} - L = \frac{y'^2}{v(y)\sqrt{1+y'^2}} - \frac{1}{v(y)}\sqrt{1+y'^2} = \frac{-1}{v(y)\sqrt{1+y'^2}} = \text{const}$$

(1) → $\underline{y(1+y'^2) = \text{const} =: c_1 < 0}$

c) substitute $y' = \cot t$, $t = \operatorname{arccot} y'$

$$\rightsquigarrow \quad y = \frac{c_1}{1+y'^2} = \frac{c_1}{1+\cot^2 t} = c_1 \sin^2 t = \frac{1}{2} c_1 (1-\cos 2t)$$

(1)

$$dx = \frac{dy}{y'} = \frac{2 c_1 \sin t \cos t \, dt}{\cot t} = 2 c_1 \sin^2 t \, dt = c_1 (1-\cos 2t)\, dt$$

$$\rightsquigarrow \quad x = c_2 + c_1 t - \frac{1}{2} c_1 \sin 2t = \frac{1}{2} c_1 (2t - \sin 2t) + c_2$$

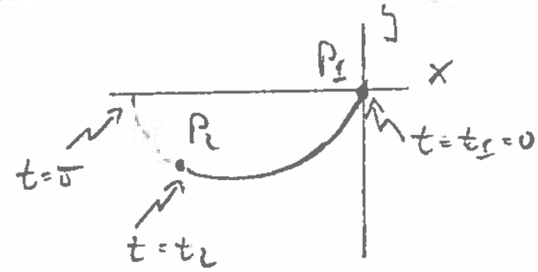
(1)

initial conditions: $y_1 = y(t=0) = 0$ ✓

$x_1 = x(t=0) = c_2 \overset{!}{=} 0 \rightsquigarrow c_2 = 0$

let $c = \frac{1}{2} c_1 \rightsquigarrow$ $\boxed{\begin{aligned} x(t) &= c(2t - \sin 2t) \\ y(t) &= c(1-\cos 2t) \end{aligned}}$ Brachistochrone in parametric form

(1)



remark: (1) This is for $x_2 < 0$

If $x_2 > 0$, consider $t < 0$

(2) c is a scale factor that must be chosen such that P_2 lies on the curve.

To bring this in standard form, let $\tau = 2t - \pi$, $\hat{x} = -x + \pi c$

$$\rightsquigarrow \quad \hat{x}(\tau) = -c(\tau + \cancel{\pi} - \sin(\tau+\pi)) + \cancel{\pi c} = -c(\tau + \sin\tau)$$

$$y(\tau) = c(1-\cos(\tau+\pi)) = c(1+\cos\tau) = -c(-1-\cos\tau)$$

cycloid

(1)

81) a) Poet(tc)

$\rightarrow$ $\boxed{\begin{array}{l} x(t) = c(2t - \sin 2t) \\ y(t) = c(1-\cos 2t) \end{array}}$ $t = \operatorname{arc\,ctg} y'$, $y' = dy/dx$

$c<0$

$\rightarrow$ $\dot{x}(t) = 2c(1-\cos 2t)$

$\dot{y}(t) = 2c \sin 2t$

$\rightarrow$ $\dot{x}^2 + \dot{y}^2 = 4c^2(1-\cos 2t)^2 + 4c^2\sin^2 2t = 4c^2 - 8c^2\cos 2t + 4c^2 = 8c^2(1-\cos 2t)$

1 $= 16c^2 \sin^2 t$

$\rightarrow$ passage time for the brachistochrone

$$\underline{T_b} = \int_0^{t_2} dt \frac{1}{\sqrt{-ay}}(-4c)\sin t = \frac{-4c}{\sqrt{-ac}} \int_0^{t_2} dt \frac{1}{\sqrt{1-\cos 2t}} \sin t$$

$$= \frac{-4c}{\sqrt{-ac}} \int_0^{t_2} dt \frac{\sin t}{\sqrt{2}\sin t} = \frac{-\sqrt{2}c}{\sqrt{-ac}} 2\int_0^{t_2} dt$$

1 $= \underline{2\sqrt{-2c/a}\; t_2}$ with $\underline{t_2 = \operatorname{arc\,ctg} y_2'}$

e) straight line: $x(\tau) = x_2\tau$, $y(\tau) = y_2\tau$, $\tau_1 = 0, \tau_2 = 1$ $(y_2<0)$

$\rightarrow$ passage time for straight line

1 $$\underline{T_s} = \int_0^1 d\tau \frac{1}{\sqrt{-ay_2\tau}} \sqrt{x_2^2+y_2^2} = \sqrt{x_2^2+y_2^2}\frac{1}{\sqrt{-ay_2}} \int_0^1 d\tau\, \tau^{-1/2} = \underline{\frac{2}{\sqrt{-ay_2}}\sqrt{x_2^2+y_2^2}}$$

But we know that the point (x_2, y_2) lies on the brachistochrone

1 c) $\rightarrow$ $x_2 = c(2t_2 - \sin 2t_2)$, $y_2 = c(1-\cos 2t_2)$

$\rightarrow$ $\underline{x_2^2 + y_2^2} = c^2(4t_2^2 - 4t_2\sin 2t_2 + \sin^2 2t_2 + 1 - 2\cos 2t_2 + \cos^2 2t_2)$

$= c^2(2(1-\cos 2t_2) + 4t_2^2 - 4t_2\sin 2t_2)$

$= c^2(4\sin^2 t_2 + 4t_2^2 - 4t_2 \sin 2t_2)$

1 $$= 4c^2\left(\sin^2 t_2 + t_2^2 - t_2 \sin 2t_2\right)$$

$$\to \quad T_s = \frac{2}{\sqrt{-ac}}\,\frac{1}{\sqrt{1-\cos 2t_2}}\,(-2c)\sqrt{\sin^2 t_2 + t_2^2 - t_2\sin 2t_2}$$

$$= \frac{+2\cdot\cancel{2}c}{\sqrt{-ac}}\,\frac{1}{\cancel{\sqrt{2}}\sin t_2}\sqrt{\sin^2 t_2 + t_2^2 - t_2 \sin 2t_2}$$

1 $$= \sqrt{-2c/a}\;\frac{+2}{\sin t_2}\sqrt{t_2^2 + \sin^2 t_2 - t_2 \sin 2t_2}$$ with t_2 from d)

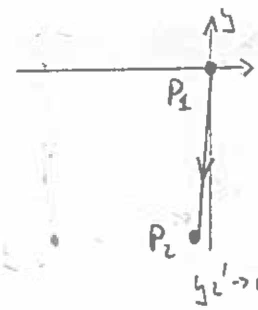
f) $t_2 \to 0$ ($\to y_2' \to \infty$)

$$T_s(t_2\to 0) = \sqrt{-2c/a}\;\frac{-2}{t_2(1+O(t_2^2))}\sqrt{\cancel{t_2^2}+\cancel{t_2^2}-\frac{2}{6}t_2^4-\cancel{2t_2^2}+\frac{8}{6}t_2^4+O(t_2^6)}$$

$$= -2\sqrt{-2c/a}\;t_2\left[1+O(t_2^2)\right]$$

1 $$= T_b\left[1+O(t_2^2)\right]$$

This is the case when the end point P_2 lies close to the fall line.

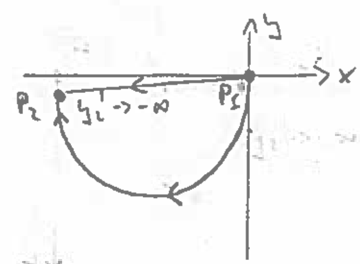


1 $\to y_2' \to \infty$, $t_2 \to 0$, and brachistochrone and straight line are almost identical.

$t_2 = -\pi - \varepsilon$ ($\to y_2' \to -\infty$)

1 $$T_s(t_2 = -\pi - \varepsilon) = \sqrt{-2c/a}\;\frac{2\pi}{\varepsilon}\left[1+O(\varepsilon^2)\right] = T_b(t_2=-\pi)\,\frac{1}{\varepsilon}\left[1+O(\varepsilon^2)\right]$$

This is the case when P_2 lies close to the x-axis $\to y_2' \to -\infty$, and the straight-line path is very slow.



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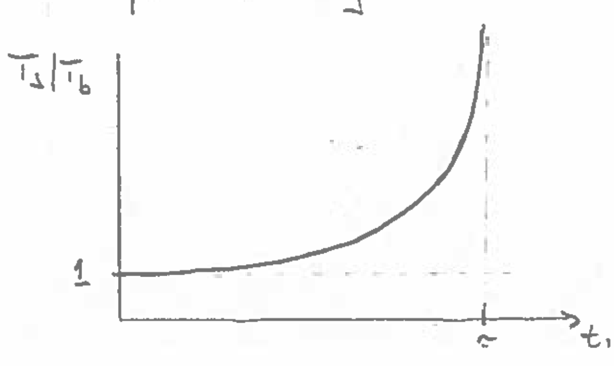


0.2.2.) cf. 0 §2.4 ex (5) $\rightsquigarrow$ $A = \frac{1}{2}\oint dt\,[x(t)\dot{y}(t) - y(t)\dot{x}(t)]$

$$\ell = \oint dt \sqrt{\dot{x}^2(t) + \dot{y}^2(t)}$$

1

cf. 0 §2.4 thm $\rightsquigarrow$ $L = \frac{1}{2}(x\dot{y} - y\dot{x}) + \frac{1}{2}\lambda\sqrt{\dot{x}^2+\dot{y}^2}$

EL eqs: $\frac{1}{2}\dot{y} = \frac{\partial L}{\partial x} = \frac{d}{dt}\frac{\partial L}{\partial \dot{x}} = -\frac{1}{2}\dot{y} + \frac{1}{2}\lambda \frac{d}{dt}\frac{\dot{x}}{\sqrt{\dot{x}^2+\dot{y}^2}}$

$$\rightsquigarrow \quad y - y_0 = \lambda \frac{\dot{x}}{\sqrt{\dot{x}^2+\dot{y}^2}} \qquad (1)$$

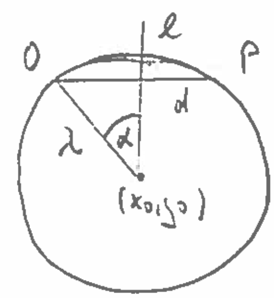
$-\frac{1}{2}\dot{x} = \frac{\partial L}{\partial y} = \frac{d}{dt}\frac{\partial L}{\partial \dot{y}} = \frac{1}{2}\dot{x} + \frac{1}{2}\lambda \frac{d}{dt}\frac{\dot{y}}{\sqrt{\dot{x}^2+\dot{y}^2}}$

1

$$\rightsquigarrow \quad x - x_0 = -\lambda \frac{\dot{y}}{\sqrt{\dot{x}^2+\dot{y}^2}} \qquad (2)$$

1

$\rightsquigarrow$ $\boxed{(x-x_0)^2 + (y-y_0)^2 = \lambda^2}$ circle with center (x_0, y_0), radius λ



Now $\overline{OP} = d = 2\lambda \sin\alpha$

and $\ell = 2\lambda\alpha$,

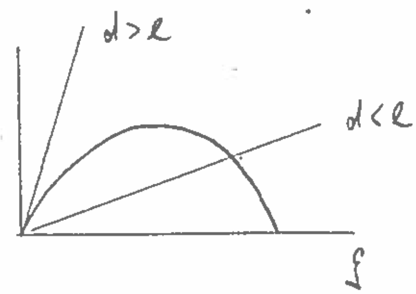
1

$\rightsquigarrow$ $\boxed{\frac{d}{2\lambda} = \sin\frac{\ell}{2\lambda}}$ determines λ

Define $\xi := \ell/2\lambda$

1

$\rightsquigarrow$ $\boxed{\sin\xi = \frac{d}{\ell}\,\xi}$.



Graphic solution $\rightsquigarrow$

1st case: $d \geq \ell$ no solution

$d < \ell$ exactly one solution, which obviously is

1

a maximum

0.2.3.) Consider a path in $\mathbb{R}_3$: $\vec{x}(t) = (x_1(t), x_2(t), x_3(t))$

length of curve: $l = \int_{t_-}^{t_+} dt \sqrt{\dot{x}_1^2(t) + \dot{x}_2^2(t) + \dot{x}_3^2(t)}$

$$= : \int_{t_-}^{t_+} dt \; L_1(\dot{\vec{x}})$$

1

Boundary condition: $x_1^2(t) + x_2^2(t) + x_3^2(t) = 1 \quad (+)$

or $0 = \int_{t_-}^{t_+} dt \left(x_1^2(t) + x_2^2(t) + x_3^2(t) - 1 \right)$

$$= : \int_{t_-}^{t_+} dt \; L_2(\vec{x})$$

1

→ consider $L = L_1 - \lambda L_2$

$$L(\vec{x}, \dot{\vec{x}}) = \sqrt{\dot{x}_1^2 + \dot{x}_2^2 + \dot{x}_3^2} - \lambda (x_1^2 + x_2^2 + x_3^2 - 1)$$

Euler-Lagrange → $\frac{d}{dt} \frac{\partial L}{\partial \dot{x}_i} = \frac{\partial L}{\partial x_i}$

$$\boxed{\frac{\dot{x}_i}{\sqrt{\dot{x}_1^2 + \dot{x}_2^2 + \dot{x}_3^2}} = -2\lambda x_i} \quad (*)$$

1

Now consider $\vec{l} := \vec{x} \times \vec{p}$ with $\vec{p} = \frac{\partial L}{\partial \dot{\vec{x}}} = \frac{\dot{\vec{x}}}{|\dot{\vec{x}}|}$

→ $\vec{p} \parallel \dot{\vec{x}}$, or $\underline{\vec{p} \times \dot{\vec{x}} = 0}$

Further, $(*)$ → $\dot{\vec{p}} = -2\lambda \vec{x}$ → $\underline{\dot{\vec{p}} \times \vec{x} = 0}$

→ $\dot{\vec{l}} = \dot{\vec{x}} \times \vec{p} + \vec{x} \times \dot{\vec{p}} = 0$ → $\vec{l}$ - const

1

and $\vec{l} \cdot \vec{x} = \vec{x} \cdot (\vec{x} \times \vec{p}) = 0$ → $\boxed{l_1 x_1 + l_2 x_2 + l_3 x_3 = 0}$ (**) with $l_{1,2,3}$ const

1

(**) describes a plane that contains the origin
(+) describes a sphere whose center is the origin } → The geodesics are great circles.