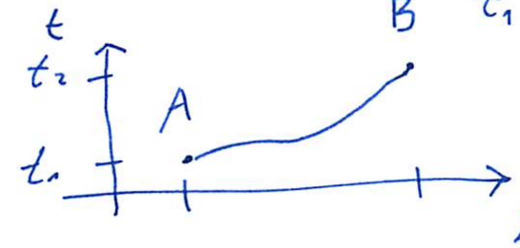
Hamiltonov princip minimalne akcije

• **Akcija S**

Vpeljemo funkcional (ki preslika funkcijo v $\mathbb{R}$),

$$S = S[\{q_i(t)\}, \{\dot{q}_i\}] = \int_{t_1}^{t_2} L(q_i(t), \dot{q}_i(t), t)\, dt.$$

za $i = 1, \dots, n$



Iščemo take poti $q_i(t)$, da bo S minimalen. Posledica so tiste, ki so rešitev E-L enačb. To je „Hamiltonov princip minimalne akcije". Kot bomo že dokazali.

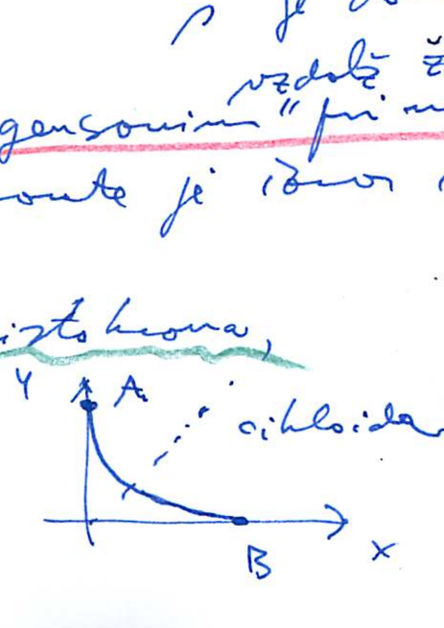
Podoben je „Fermatov" princip, ki pravi, da se (EM) valovanje širi tako, da „žarek" pride na cilj v minimalnem času oz. da je „faza" minimalna v optično nehomogenem sredstvu,

$$T = \int_{\text{od A do B}} dt = \int \frac{1}{c}\frac{c}{v}\frac{ds}{dt}\, dt = \frac{1}{c}\int_A^B n(s)\, ds$$

s je dolžina poti vzdolž žarka.

V močni zvezi s „Huygensovim" principom: vsaka točka valovne fronte je izvor valovanja s hitrostjo c. Optika.

zgodovinsko: brahistohrona,



Variacijsko iskanje minimuma

$$I = \int_{x_1}^{x_2} f(y, y', x)\,dx = \text{ekstrem}, \qquad y' = \frac{dy}{dx}$$

na robu je

$$y(x_1) = y_1$$

$$y(x_2) = y_2 .$$

Nastavek,

$$y(x,\alpha) = y(x,0) + \alpha\,\eta(x) \quad ; \quad y(x,0) = y(x),$$

$\eta(x)$ je poljubna gladka funkcija, na robu $\eta(x_1) = \eta(x_2) = 0$. Torej je $I = I(\alpha)$ in iščemo minimum,

$$\frac{dI(\alpha)}{d\alpha} = \int_{x_1}^{x_2} \Big(\frac{\partial f}{\partial y} \underbrace{\frac{\partial y}{\partial \alpha}}_{\eta(x)} + \frac{\partial f}{\partial y'} \frac{\partial y'}{\partial \alpha} \Big) dx = 0$$

$$\int_{x_1}^{x_2} \frac{\partial f}{\partial y'} \underbrace{\underbrace{\frac{\partial y'}{\partial \alpha}}_{\eta'}}_{d\eta} dx = \underbrace{\frac{\partial f}{\partial y'} \eta(x) \Big|_{x_1}^{x_2}}_{=0 \text{ po predpostavki}} - \int_{x_1}^{x_2} \eta(x) \frac{d}{dx} \frac{\partial f}{\partial y'}\, dx$$

Torej,

$$\frac{dI}{d\alpha} = \int_{x_1}^{x_2} \Big(\frac{\partial f}{\partial y} - \frac{d}{dx} \frac{\partial f}{\partial y'} \Big) \eta(x)\, dx = 0,$$

kar velja za $\forall\ \eta(x)$, zato

$$\boxed{\frac{d}{dx} \frac{\partial f}{\partial y'} - \frac{\partial f}{\partial y} = 0 .}$$

Variacijska izpeljava Euler-Lagrangevih enačb

Sedaj pa to enostavno ponovimo za q_i in S, $\quad \dot q_i \quad \delta \dot q_i = \alpha \dot\eta_i(t)$

$$q_i(t,\alpha) = \underbrace{q_i(t)}_{\text{iskana rešitev}} + \alpha\,\eta_i(t) = q_i(t) + \underbrace{\delta q_i(t)}_{\text{variacija}}$$

Tako kot prej je $\delta q_i(t_1) = \delta q_i(t_2) = 0$,

$$\delta S = \int_{t_1}^{t_2} \Big(\sum_i \frac{\partial L}{\partial q_i}\delta q_i + \underbrace{\sum_i \frac{\partial L}{\partial \dot q_i}\delta \dot q_i}_{*} \Big)\,dt = 0 \qquad (\alpha \to 0)$$

$$* \int_{t_1}^{t_2} \frac{\partial L}{\partial \dot q_i}\delta \dot q_i\,dt = \frac{\partial L}{\partial \dot q_i}\delta q_i\Big|_{t_1}^{t_2} - \int_{t_1}^{t_2} \delta q_i \frac{d}{dt}\frac{\partial L}{\partial \dot q_i}\,dt \,,$$

$$\delta S = \int_{t_1}^{t_2} \sum_i \Big(\frac{\partial L}{\partial q_i} - \frac{d}{dt}\frac{\partial L}{\partial \dot q_i} \Big)\delta q_i\,dt = 0 \quad \text{za } \forall\, \delta q_i$$

$$\Rightarrow \boxed{\frac{d}{dt}\frac{\partial L}{\partial \dot q_i} - \frac{\partial L}{\partial q_i} = 0.}$$

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spomnimo se $\quad L' = L + \frac{d}{dt}F(q_i,t)$

$$S' = \int_{t_1}^{t_2} L'\,dt = \int_{t_1}^{t_2} L\,dt + \int_{t_1}^{t_2} \frac{d}{dt}F\,dt = S + F(q_i(t),t)\Big|_{t_1}^{t_2}$$

$$\delta S' = \delta S + \underbrace{\delta F\Big|_{t_1}^{t_2}}_{} \quad \Rightarrow \quad \delta S' = \delta S \ \text{ pri istih } q_i(t).$$

$$\delta F\Big|_{t_1}^{t_2} = \sum_i \frac{\partial F}{\partial q_i}\underbrace{\delta q_i(t)\Big|_{t_1}^{t_2}}_{=0} = 0$$

Železni repertoar: centralni potencial, nitovka, majhna nihanja.

Enodimenzionalni primeri,

$$L = \frac{1}{2} m(q)\, \dot{q}^2 - U(q).$$

Vemo že, da velja

$$E = T + U = \frac{1}{2} m(q)\, \dot{q}^2 + U(q) = \text{konst.},$$

torej

$$\frac{dq}{dt} = \dot{q} = \sqrt{\frac{2(E - U(q))}{m(q)}}$$

in

$$\int_{t_1}^{t_2} dt = \int_{q_1}^{q_2} \sqrt{\frac{m(q)}{2(E - U(q))}}\, dq \Rightarrow q_2(t_2) \text{ pri}$$

$t_2 - t_1 = f(q_2)$.

začetnem pogoju $q(t_1) = q_1$

Torej je tu skupina problemov vedno rešljiva z direktno integracijo. Jasno, da ni vedno elementarno rešljivo, numerično pa.

Primer: $q = x$, $m(q) = m$ masa

$$E = \frac{1}{2} m v^2 + U(x)$$

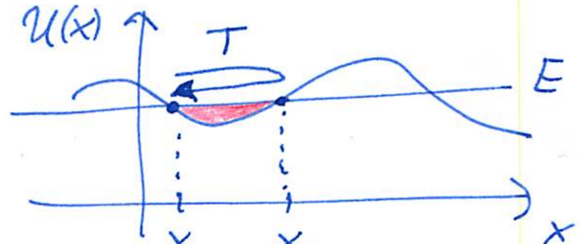
$$\pm \frac{dx}{dt} = \sqrt{2(E - U(x))/m}$$

dve rešitvi →

$$\boxed{\pm}\, t = \sqrt{\frac{m}{2}} \left| \int_{x_1}^{x(t)} \frac{dx}{\sqrt{E - U(x)}} \right| \quad \text{pri } x(0) = x_1.$$

nihajni čas: T_0

$$T_0 = 2\sqrt{\frac{m}{2}} \left| \int_{x_1(E)}^{x_2(E)} \frac{dx}{\sqrt{E - U(x)}} \right|$$



obračalni točki

konkretno: navadno nihalo.

$$L = \frac{1}{2}ml^2\dot{\varphi}^2 + mgl\cos\varphi$$

= konst.

$$E = \frac{1}{2}ml^2\dot{\varphi}^2 - mgl\cos\varphi = E_0 = -mgl\cos\varphi_0$$

$(\varphi = \varphi_0$ in $\dot{\varphi} = 0)$.

Nihajni čas T_0 je $4\times$ čas od $\varphi=0$ do $\varphi=\varphi_0$,

$\sin^2\frac{\varphi}{2} = \frac{1}{2}(1-\cos\varphi)$

$$T_0 = 4\sqrt{\frac{l}{2g}}\left|\int_0^{\varphi_0}\frac{d\varphi}{\sqrt{\cos\varphi-\cos\varphi_0}}\right| =$$

$$= 2\sqrt{\frac{l}{g}}\int_0^{\varphi_0}\frac{d\varphi}{\sqrt{\sin^2\frac{\varphi_0}{2}-\sin^2\frac{\varphi}{2}}} =$$

$$= 4\sqrt{\frac{l}{g}}\,K(\underbrace{\sin\tfrac{1}{2}\varphi_0}_{k}),\text{ kjer je}$$

$$K(k) = \int_0^{\frac{\pi}{2}}\frac{d\xi}{\sqrt{1-k^2\sin^2\xi}}\ ;\ \sin\xi = \frac{\sin\varphi/2}{\sin\varphi_0/2}$$

popolni eliptični integral I. vrste.

Če $k \ll 1$, $\sin\frac{\varphi_0}{2}\approx\frac{\varphi_0}{2}$, velja

$$\boxed{T = 2\pi\sqrt{l/g}\left(1+\frac{\varphi_0^2}{16}+\mathcal{O}(\varphi_0^4)\right).}$$

in tudi za $\varphi, \varphi_0 \ll 1$,

$$T_0 = 2\sqrt{\frac{l}{g}}\int_0^{\varphi_0}\frac{d\varphi}{\sqrt{\frac{\varphi_0^2}{4}-\frac{\varphi^2}{4}}} = 4\underbrace{\sqrt{\frac{l}{g}}}_{\frac{1}{\omega}}\int_0^{\varphi_0}\frac{d\varphi}{\sqrt{\varphi_0^2-\varphi^2}} = \frac{4\cdot 1}{\omega}\arcsin\varphi/\varphi_0 =$$

$$= \frac{4\cdot 1}{\omega}\arcsin 1 = \frac{4\cdot 1}{\omega}\frac{\pi}{2}.$$

$$\Rightarrow \boxed{T_0 = 4\cdot\sqrt{\frac{l}{g}}\,\frac{\pi}{2} = 2\pi\sqrt{\frac{l}{g}} = \frac{2\pi}{\omega}}$$

$$\int\frac{dx}{\sqrt{a^2-x^2}} = \arcsin x/a$$

Osnovni primer: harmonski oscilator

$$\boxed{E = \frac{1}{2} m\dot{x}^2 + \frac{1}{2} k x^2 = E_0 = \text{konst.}}$$

E_0 je konstanta, odvisna od začetnih pogojev

najprej izrazimo hitrost $\dot{x}(t)$,

$$\dot{x}(t) = \frac{dx}{dt} = \pm\sqrt{\frac{2E_0 - x(t)^2}{m}}$$

predznak glede na začetne pogoje (smer hitrosti)

Primer: $x(0) = x_0$

$\dot{x}(0) = 0 \quad ; \quad \omega^2 = \frac{k}{m}$

$$\omega \int_0^t dt = - \int_{x_0}^{x(t)} \frac{dx}{\sqrt{x_0^2 - x^2}} = - \arcsin \frac{x(t)}{x_0} - \underbrace{\arcsin 1}_{\pi/2}$$

$$x_0 \sin\left(\frac{\pi}{2} - \omega t\right) = x(t)$$

$\hookrightarrow \sin\frac{\pi}{2}\cos\omega t - \cos\frac{\pi}{2}\sin\omega t$

$$\Rightarrow \boxed{x(t) = x_0 \cos\omega t.}$$

Analogno se postopa pri drugih začetnih pogojih.

$\sin(\alpha \pm \beta) = \sin\alpha\cos\beta \pm \cos\alpha\sin\beta$