

2-3. Find  $S_{cl}$  for a particle under a constant force  $f$ , that is,

$$L = \frac{m}{2}\dot{x}^2 + fx$$

From the above Lagrangian we have

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

and

$$\frac{\partial L}{\partial x} = f$$

By equation (2.7) which is

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

we have

$$\ddot{x} = \frac{f}{m}$$

Hence  $x(t)$  must have the following quadratic form.

$$x(t) = \frac{f}{2m}t^2 + Bt + C$$

We have the following boundary conditions.

$$\begin{aligned}x(t_a) &= x_a \\x(t_b) &= x_b\end{aligned}$$

Subtract to cancel  $C$ .

$$x(t_b) - x(t_a) = \frac{f}{2m}(t_b^2 - t_a^2) + B(t_b - t_a) = x_b - x_a$$

Solve for  $B$ .

$$B = \frac{x_b - x_a}{t_b - t_a} - \frac{f(t_b^2 - t_a^2)}{2m(t_b - t_a)}$$

Solve for  $C$ .

$$\begin{aligned}C &= x_a - \frac{f}{2m}t_a^2 - Bt_a \\&= \frac{f(t_at_b^2 - t_a^2t_b)}{2m(t_b - t_a)} + \frac{t_bx_a - t_ax_b}{t_b - t_a}\end{aligned}$$

Altogether we have

$$x(t) = \frac{f}{2m}t^2 + \left( \frac{x_b - x_a}{t_b - t_a} - \frac{f(t_b^2 - t_a^2)}{2m(t_b - t_a)} \right) t + \frac{f(t_a t_b^2 - t_a^2 t_b)}{2m(t_b - t_a)} + \frac{t_b x_a - t_a x_b}{t_b - t_a} \quad (1)$$

Equation (1) is too complicated to continue so we now translate the time coordinate as

$$\begin{aligned} t_a &= 0 \\ t_b &= T \end{aligned}$$

We now have

$$x(t) = \frac{ft^2}{2m} + \left( \frac{x_b - x_a}{T} - \frac{fT}{2m} \right) t + x_a \quad (2)$$

Differentiate  $x(t)$  to obtain  $\dot{x}(t)$ .

$$\dot{x}(t) = \frac{d}{dt}x(t) = \frac{ft}{m} - \frac{fT}{2m} + \frac{x_b - x_a}{T} \quad (3)$$

The new Lagrangian is

$$\begin{aligned} L &= \frac{m}{2}\dot{x}(t)^2 + fx(t) \\ &= \frac{f^2}{m}t^2 + \left( \frac{2f(x_b - x_a)}{T} - \frac{f^2T}{m} \right) t + \frac{f^2T^2}{8m} + \frac{f(3x_a - x_b)}{2} + \frac{m(x_b - x_a)^2}{2T^2} \end{aligned} \quad (4)$$

Hence

$$S_{cl} = \int_0^T L dt = \frac{m(x_b - x_a)^2}{2T} + \frac{fT(x_b + x_a)}{2} - \frac{f^2T^3}{24m} \quad (5)$$

where  $T = t_b - t_a$ .