

2-4. Classically, the momentum is defined as

$$p = \frac{\partial L}{\partial \dot{x}} \quad (2.10)$$

Show that the momentum at a final point is

$$\left( \frac{\partial L}{\partial \dot{x}} \right)_{x=x_b} = + \frac{\partial S_{cl}}{\partial x_b} \quad (2.11)$$

while the momentum at an initial point is

$$\left( \frac{\partial L}{\partial \dot{x}} \right)_{x=x_a} = - \frac{\partial S_{cl}}{\partial x_a}$$

*Hint:* Consider the effect on equation (2.6) of a change in the end points.

$$\delta S = \left( \delta x(t) \frac{\partial L}{\partial \dot{x}} \right)_{t_a}^{t_b} - \int_{t_a}^{t_b} \delta x(t) \left( \frac{d}{dt} \frac{\partial L}{\partial \dot{x}} - \frac{\partial L}{\partial x} \right) dt \quad (2.6)$$

Consider equation (2.7) for the classical path.

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{x}} - \frac{\partial L}{\partial x} = 0 \quad (2.7)$$

Substitute (2.7) into (2.6) to obtain

$$\delta S_{cl} = \left( \delta x(t) \frac{\partial L}{\partial \dot{x}} \right)_{t_a}^{t_b} = \delta x_b \left( \frac{\partial L}{\partial \dot{x}} \right)_{x=x_b} - \delta x_a \left( \frac{\partial L}{\partial \dot{x}} \right)_{x=x_a} \quad (1)$$

For the endpoints  $x_a$  and  $x_b$  we have  $\delta S_{cl} = 0$  by equation (2.3).

$$\delta x(t_a) = \delta x(t_b) = 0 \quad (2.3)$$

However, consider a variation of the endpoint  $x_b$ . Then by equation (1)

$$\delta S_{cl} = \delta x_b \left( \frac{\partial L}{\partial \dot{x}} \right)_{x=x_b}$$

Hence

$$\lim \frac{\delta S_{cl}}{\delta x_b} = \frac{\partial S_{cl}}{\partial x_b} = \left( \frac{\partial L}{\partial \dot{x}} \right)_{x=x_b}$$

Likewise, a variation of  $x_a$  yields

$$\lim \frac{\delta S_{cl}}{\delta x_a} = \frac{\partial S_{cl}}{\partial x_a} = - \left( \frac{\partial L}{\partial \dot{x}} \right)_{x=x_a}$$