3-9. Find the kernel for a particle in a constant field f where the Lagrangian is

$$L = \frac{m}{2}\dot{x}^2 + fx \tag{3.61}$$

The result is

$$K = \left(\frac{m}{2\pi i\hbar T}\right)^{1/2} \exp\left(\frac{i}{\hbar}\left(\frac{m(x_b - x_a)^2}{2T} + \frac{fT(x_b + x_a)}{2} - \frac{f^2T^3}{24m}\right)\right) \tag{3.62}$$

where $T = t_b - t_a$.

From problem 2-3 we have for the action S

$$S(b,a) = \frac{m(x_b - x_a)^2}{2T} + \frac{fT(x_b + x_a)}{2} - \frac{f^2T^3}{24m} \tag{1}$$

where $T = t_b - t_a$.

Consider equation (3.51).

$$K(b,a) = F(T)\exp\left(\frac{iS(b,a)}{\hbar}\right) \tag{3.51}$$

Substitute (1) into (3.51).

$$K(b,a) = F(T)\exp\left(\frac{im(x_b - x_a)^2}{2\hbar T} + \frac{ifT(x_b + x_a)}{2\hbar} - \frac{if^2T^3}{24\hbar m}\right) \tag{2}$$

We now proceed to solve for $F(T)$. Consider equation (2.31).

$$K(b,a) = \int_{-\infty}^{\infty} K(b,c)K(c,a)\,dx_c \tag{2.31}$$

Substitute (3.51) into (2.31) to obtain

$$K(b,a) = F(t_b - t_c)F(t_c - t_a)\int_{-\infty}^{\infty} \exp\left(\frac{iS(b,c)}{\hbar} + \frac{iS(c,a)}{\hbar}\right) dx_c \tag{3}$$

Substitute (1) into (3) and rewrite the result as powers of x_c.

$$K(b,a) = F(t_b - t_c)F(t_c - t_a)\exp\left(-\frac{if^2(t_b - t_c)^3}{24\hbar m} - \frac{if^2(t_c - t_a)^3}{24\hbar m}\right) \times \int_{-\infty}^{\infty} \exp\left(Ax_c^2 + Bx_c + C\right) dx_c \tag{4}$$

where

$$A = \frac{im}{2\hbar}\left(\frac{1}{t_b - t_c} + \frac{1}{t_c - t_a}\right) \tag{5}$$

$$B = \frac{ifT}{2\hbar} - \frac{im}{\hbar}\left(\frac{x_b}{t_b - t_c} + \frac{x_a}{t_c - t_a}\right) \tag{6}$$

$$C = \frac{if}{2\hbar}\big(x_b(t_b - t_c) + x_a(t_c - t_a)\big) + \frac{im}{2\hbar}\left(\frac{x_b^2}{t_b - t_c} + \frac{x_a^2}{t_c - t_a}\right) \tag{7}$$

Note that the exponential involving f^2 is independent of x_c and is factored out of the integrand in (4).

Solve the integral in (4).

$$\begin{aligned}\int_{-\infty}^{\infty} \exp(Ax_c^2 + Bx_c + C)\,dx_c &= \left(-\frac{\pi}{A}\right)^{1/2} \exp\left(-\frac{B^2}{4A} + C\right)\\ &= \left(-\frac{2\pi\hbar(t_b - t_c)(t_c - t_a)}{imT}\right)^{1/2}\\ &\quad\times \exp\left(\frac{im(x_b - x_a)^2}{2\hbar T} + \frac{ifT(x_b + x_a)}{2\hbar} - \frac{if^2T(t_b - t_c)(t_c - t_a)}{8\hbar m}\right)\end{aligned} \tag{8}$$

Substitute (8) into (4) to obtain

$$\begin{aligned}K(b,a) &= F(t_b - t_c)F(t_c - t_a)\exp\left(-\frac{if^2(t_b - t_c)^3}{24\hbar m} - \frac{if^2(t_c - t_a)^3}{24\hbar m}\right)\\ &\quad\times \left(-\frac{2\pi\hbar(t_b - t_c)(t_c - t_a)}{imT}\right)^{1/2}\\ &\quad\times \exp\left(\frac{im(x_b - x_a)^2}{2\hbar T} + \frac{ifT(x_b + x_a)}{2\hbar} - \frac{if^2T(t_b - t_c)(t_c - t_a)}{8\hbar m}\right)\end{aligned} \tag{9}$$

Note that

$$T^3 = (t_b - t_c)^3 + (t_c - t_a)^3 + 3T(t_b - t_c)(t_c - t_a) \tag{10}$$

Use (10) to combine exponentials involving f^2 in (9).

$$\begin{aligned}K(b,a) &= F(t_b - t_c)F(t_c - t_a)\\ &\quad\times \left(-\frac{2\pi\hbar(t_b - t_c)(t_c - t_a)}{imT}\right)^{1/2}\\ &\quad\times \exp\left(\frac{im(x_b - x_a)^2}{2\hbar T} + \frac{ifT(x_b + x_a)}{2\hbar} - \frac{if^2T^3}{24\hbar m}\right)\end{aligned} \tag{11}$$

Equating (2) with (11) cancels the exponentials and leaves

$$F(T) = F(t_b - t_c)F(t_c - t_a)\left(-\frac{2\pi\hbar(t_b - t_c)(t_c - t_a)}{imT}\right)^{1/2} \tag{12}$$

From problem 3-7, let

$$F(t) = \left(\frac{m}{2\pi i\hbar t}\right)^{1/2} g(t) \tag{13}$$

Substitute (13) into (12) to obtain

$$\left(\frac{m}{2\pi i\hbar T}\right)^{1/2} g(T) = \left(\frac{m}{2\pi i\hbar(t_b - t_c)}\right)^{1/2} g(t_b - t_c) \times \left(\frac{m}{2\pi i\hbar(t_c - t_a)}\right)^{1/2} g(t_c - t_a)\left(-\frac{2\pi\hbar(t_b - t_c)(t_c - t_a)}{imT}\right)^{1/2}$$

The coefficients cancel leaving

$$g(T) = g(t_b - t_c)g(t_c - t_a) \tag{14}$$

Hence

$$g(t) = 1$$

and

$$F(T) = \left(\frac{m}{2\pi i\hbar T}\right)^{1/2} \tag{15}$$

Substitute (15) into (2).

$$K(b,a) = \left(\frac{m}{2\pi i\hbar T}\right)^{1/2} \exp\left(\frac{im(x_b - x_a)^2}{2\hbar T} + \frac{ifT(x_b + x_a)}{2\hbar} - \frac{if^2T^3}{24\hbar m}\right)$$