



## 12. Lagrangian densities (23 points)

To be discussed on Wednesday, 21<sup>st</sup> January, 2026 in the tutorial.

Please indicate your preferences until Friday, 16/01/2026, 21:00:00 on the website.

### Exercise 12.1: Equations of motion

Find the Euler-Lagrange equations for the following Lagrangian densities:

a) (2 points)

$$\mathcal{L} = -(\partial_\mu A^\nu)(\partial_\nu A^\mu) + \frac{1}{2}m^2 A_\mu A^\mu + \frac{\lambda}{2}(\partial_\mu A^\mu)^2.$$

b) (2 points)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}A_\mu A^\mu,$$

where  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ .

c) (2 points)

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}\phi^2 - \frac{\lambda}{4}\phi^4,$$

where  $\phi(x)$  is a real scalar field.

d) (2 points)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (\partial_\mu \phi - ieA_\mu \phi)(\partial^\mu \phi^* + ieA^\mu \phi^*) - \frac{1}{2}m^2 \phi^* \phi,$$

where  $\phi(x)$  is a complex scalar field.

### Exercise 12.2: Equation of motion invariance

a) (4 points) Show that when the divergence of an arbitrary field function  $f^\mu(\phi_i)$  is added to a Lagrangian density, its equations of motion remain unchanged.

*Hint: Assume that the variation commutes with the partial derivatives and the variation of the fields  $\phi_i$  vanish at infinity.*

### Exercise 12.3: Equation of motion invariance

The Lagrangian density of a real three component scalar field is given in the following form

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2}m^2 \phi^T \phi, \quad \phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix},$$

where  $T$  denotes transposition.

a) (2 points) Find the equations of motion.  
b) (3 points) Check if  $\mathcal{L}$  is invariant under  $SO(3)$ .

*Hint: Assume rigid solutions, that is for  $R$  being an  $SO(3)$  rotation matrix,  $\partial_\mu R = 0$  holds. The rotation matrices are given by*

$$R_1(\alpha_1) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha_1 & -\sin \alpha_1 \\ 0 & \sin \alpha_1 & \cos \alpha_1 \end{pmatrix} = e^{\alpha_1 T_1},$$

$$R_2(\alpha_2) = \begin{pmatrix} \cos \alpha_2 & 0 & \sin \alpha_2 \\ 0 & 1 & 0 \\ -\sin \alpha_2 & 0 & \cos \alpha_2 \end{pmatrix} = e^{\alpha_2 T_2},$$

$$R_3(\alpha_3) = \begin{pmatrix} \cos \alpha_3 & -\sin \alpha_3 & 0 \\ \sin \alpha_3 & \cos \alpha_3 & 0 \\ 0 & 0 & 1 \end{pmatrix} = e^{\alpha_3 T_3}.$$

We are now going to find the Noether currents, which are given by

$$J_a^\mu = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_b)} \left( \frac{\delta \phi_b}{\delta \omega^a} - \frac{\delta x^\mu}{\delta \omega^a} \partial_\mu \phi_b \right) + \mathcal{L} \frac{\delta x^\mu}{\delta \omega^a}, \quad a = 1, 2, 3.$$

c) (3 points) Prove

$$\delta \phi_a = \phi'_a - \phi_a = \epsilon_{abc} \alpha^b \phi^c.$$

*Hint: Show that the transformed under  $SO(3)$  fields for small  $\alpha_i$  can be written as*

$$\phi'_a \simeq \phi_a + \delta \omega_i \cdot (T_i)^b_a \phi_b,$$

where

$$R_i(\omega_i) = e^{\delta \omega_i T_i}, \quad T_i = \left. \frac{\partial R_i}{\partial \alpha_i} \right|_{\alpha_i=0}.$$

d) (3 points) Show that the Noether currents can be compactly written as

$$J_a^\mu = \epsilon_{abc} \phi^b \partial^\mu \phi^c.$$