

# Exercises to “Standard Model of Particle Physics II”

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**Lecture webpage:** <https://www.mpi-hd.mpg.de/manitop/StandardModel2/index.html>

**Hand-in of solutions:**

October 26, 2022 - 09:15, Phil. 12, kHS

**Discussion of solutions:**

October 26, 2022 - 11:15, Phil. 12, R105

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## Problem 1: General Global symmetry transformations [5 Points]

- a) Derive the Noether theorem for a global symmetry transformation of the following Lagrange density:

$$\mathcal{L} = \mathcal{L}(u_i, \partial_\mu u_i)$$

In other words, find an expression for the conserved current associated to the symmetry of the theory under the field transformation:

$u_i(x) \rightarrow u'_i(x) = e^{i\epsilon_k T_{ij}^k} u_j(x) \cong u_i(x) + \delta u_i(x)$  with  $\delta u_i(x) = i\epsilon_k T_{ij}^k u_j(x)$ . Here the  $T_{ij}^k$  denote the generators of the algebra of the corresponding symmetry group and  $\epsilon_k$  the infinitesimal, space-time independent coefficients.

- b) Apply your formula to the Lagrange density of a massive complex scalar field (where we consider  $\phi$  and  $\phi^*$  as independent fields):

$$\mathcal{L} = (\partial_\mu \phi)(\partial^\mu \phi^*) - m^2 \phi^* \phi$$

What is the conserved current in this case?

*Hint:* Use  $\phi(x) \rightarrow \phi'(x) = e^{i\epsilon} \phi(x)$  as transformation of the scalar field.

## Problem 2: Local symmetry transformations in QED [5 Points]

Show that the Lagrange density of QED

$$\mathcal{L}_{\text{QED}} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu},$$

with  $D_\mu = \partial_\mu - ieA_\mu$  and  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ , is invariant under the local symmetry transformations

$$\psi \rightarrow \psi' = e^{i\epsilon(x)}\psi, \quad \bar{\psi} \rightarrow \bar{\psi}' = \bar{\psi}e^{-i\epsilon(x)},$$

$$A_\mu \rightarrow A'_\mu = A_\mu + \frac{1}{e}\partial_\mu \epsilon(x).$$

Local symmetry means that now the infinitesimal parameter  $\epsilon(x)$  depend on the space-time coordinates.

**Problem 3: General local symmetry transformations [10 Points]**

Now, we want the general Lagrange density  $\mathcal{L} = \mathcal{L}(u_i, \partial_\mu u_i)$  to be invariant under a local symmetry transformation. In analogy with **Problem 1**, the fields  $u_i$  transform as

$$u_i(x) \rightarrow u'_i(x) = e^{i\epsilon_k(x)T_{ij}^k} u_j(x) \cong u_i(x) + \delta u_i(x)$$

with

$$\delta u_i(x) = i\epsilon_k(x)T_{ij}^k u_j(x).$$

- a) Considering the transformation properties of the  $u_i$ 's given above, show that we need to introduce a new field to keep  $\mathcal{L}$  invariant under the local symmetry transformation.
- b) Extend the system by a set of additional vector fields  $A_{\mu k}$  (one for each generator  $T_{ij}^k$ ), so that the Lagrange density does not depend on their derivatives:  $\mathcal{L} = \mathcal{L}(u_i, \partial_\mu u_i, A_{\mu k})$ . Assume that the transformation properties of the new fields are of the following form (where  $P$  and  $R$  denote, at first, unspecified matrices):

$$A_{\mu l}(x) \rightarrow A'_{\mu l}(x) = A_{\mu l}(x) + P_{lm}^k A_{\mu m}(x)\epsilon_k(x) + R_l^k \partial_\mu \epsilon_k(x).$$

From the variational principle, derive general conditions for the matrices  $P$  and  $R$  such that  $\mathcal{L}(u_i, \partial_\mu u_i, A_{\mu k})$  is invariant under local symmetry transformations.

- c) Consider the following Lagrange density

$$\mathcal{L} = \frac{1}{2}(D_\mu u_i)(D^\mu u_i),$$

where the covariant derivative of the fields  $u_i$  is given by  $D_\mu u_i = \partial_\mu u_i + g\epsilon_{ijk}A_{\mu j}u_k$  and  $\epsilon_{ijk}$  denotes the totally anti-symmetric tensor. Taking into account the results from b) find a relation between the matrix  $R_l^k$  and the generators  $T_{ij}^k$ .