

1. According to the Noether theorem, a translationally invariant system of classical fields  $\phi_a(x)$  has a conserved stress-energy tensor

$$T_{\text{Noether}}^{\mu\nu} = \sum_a \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_a)} \partial^\nu \phi^a - g^{\mu\nu} \mathcal{L}. \quad (1)$$

Actually, to assure the symmetry of the stress-energy tensor,  $T^{\mu\nu} = T^{\nu\mu}$  (which is necessary for the angular momentum conservation), one sometimes has to add a total divergence,

$$T^{\mu\nu} = T_{\text{Noether}}^{\mu\nu} + \partial_\lambda \mathcal{K}^{\lambda\mu\nu}, \quad (2)$$

where  $\mathcal{K}^{\lambda\mu\nu} \equiv -\mathcal{K}^{\mu\lambda\nu}$  is some 3-index Lorentz tensor antisymmetric in its first two indices.

- (a) Show that regardless of the specific form of the  $\mathcal{K}^{\lambda\mu\nu}(\phi, \partial\phi)$  as a function of the fields and their derivatives, we have

$$\begin{aligned} \partial_\mu T^{\mu\nu} &= \partial_\mu T_{\text{Noether}}^{\mu\nu} = (\text{hopefully}) = 0 \\ \text{and } P_{\text{net}}^\mu &\equiv \int d^3\mathbf{x} T^{0\mu} = \int d^3\mathbf{x} T_{\text{Noether}}^{0\mu}. \end{aligned} \quad (3)$$

Note: Assume that all the fields go to zero for  $|\mathbf{x}| \rightarrow \infty$  fast enough that all the surface integrals over the boundary of 3D space vanish when we push the boundary to infinity.

For the scalar fields, real or complex,  $T_{\text{Noether}}^{\mu\nu}$  is properly symmetric and one simply has  $T^{\mu\nu} = T_{\text{Noether}}^{\mu\nu}$ . Unfortunately, the situation is more complicated for the vector, tensor or spinor fields. To illustrate the problem, consider the free electromagnetic fields described by the Lagrangian

$$\mathcal{L}(A_\mu, \partial_\nu A_\mu) = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \quad (4)$$

where  $A_\mu$  is a real vector field and  $F_{\mu\nu} \stackrel{\text{def}}{=} \partial_\mu A_\nu - \partial_\nu A_\mu$ .

- (b) Write down  $T_{\text{Noether}}^{\mu\nu}$  for the free electromagnetic fields and show that it is neither symmetric nor gauge invariant.
- (c) The properly symmetric — and also gauge invariant — stress-energy tensor for the free electromagnetism is

$$T_{\text{EM}}^{\mu\nu} = -F^{\mu\lambda}F^{\nu}_{\lambda} + \frac{1}{4}g^{\mu\nu}F_{\kappa\lambda}F^{\kappa\lambda}. \quad (5)$$

Show that this expression indeed has form (2) for some  $\mathcal{K}^{\lambda\mu\nu}$ .

- (d) Write down the components of the stress-energy tensor (5) in non-relativistic notations and make sure you have the familiar electromagnetic energy density, momentum density and pressure.

Finally, consider the electromagnetic fields coupled to the electric current  $J^\mu$  of some charged “matter” fields. Because of this coupling, only the *net* energy-momentum of the whole field system should be conserved, but not the separate  $P_{\text{EM}}^\mu$  and  $P_{\text{mat}}^\mu$ . Consequently, we should have

$$\partial_\mu T_{\text{net}}^{\mu\nu} = 0 \quad \text{for} \quad T_{\text{net}}^{\mu\nu} = T_{\text{EM}}^{\mu\nu} + T_{\text{mat}}^{\mu\nu} \quad (6)$$

but generally  $\partial_\mu T_{\text{EM}}^{\mu\nu} \neq 0$  and  $\partial_\mu T_{\text{mat}}^{\mu\nu} \neq 0$ .

- (e) Use Maxwell’s equations to show that

$$\partial_\mu T_{\text{EM}}^{\mu\nu} = -F^{\nu\lambda}J_\lambda \quad (7)$$

and therefore any system of charged matter fields should have its stress-energy tensor related to the electric current  $J_\lambda$  according to

$$\partial_\mu T_{\text{mat}}^{\mu\nu} = +F^{\nu\lambda}J_\lambda. \quad (8)$$

2. Continuing problem 1, consider the EM fields coupled to a specific model of charged matter, namely a complex scalar field  $\Phi(x) \neq \Phi^*(x)$  of electric charge  $q \neq 0$ . Altogether, the net Lagrangian for the  $A^\mu$ ,  $\Phi$ , and  $\Phi^*$  fields is

$$\mathcal{L}_{\text{net}} = D^\mu \Phi^* D_\mu \Phi - m^2 \Phi^* \Phi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \quad (9)$$

where

$$D_\mu \Phi = (\partial_\mu + iqA_\mu)\Phi \quad \text{and} \quad D_\mu \Phi^* = (\partial_\mu - iqA_\mu)\Phi^* \quad (10)$$

are the *covariant* derivatives.

- (a) Write down the equation of motion for all fields in a covariant form. Also, write down the electric current

$$J^\mu \stackrel{\text{def}}{=} -\frac{\partial \mathcal{L}}{\partial A_\mu} \quad (11)$$

in a manifestly gauge-invariant form and verify its conservation,  $\partial_\mu J^\mu = 0$  (as long as the scalar fields satisfy their equations of motion).

- (b) Write down the Noether stress-energy tensor for the whole system and show that

$$T_{\text{net}}^{\mu\nu} \equiv T_{\text{EM}}^{\mu\nu} + T_{\text{mat}}^{\mu\nu} = T_{\text{Noether}}^{\mu\nu} + \partial_\lambda \mathcal{K}^{\lambda\mu\nu}, \quad (12)$$

where  $T_{\text{EM}}^{\mu\nu}$  is exactly as in eq. (5) for the free EM fields, the improvement tensor  $\mathcal{K}^{\lambda\mu\nu} = -\mathcal{K}^{\mu\lambda\nu}$  is also exactly as in problem 1, and

$$T_{\text{mat}}^{\mu\nu} = D^\mu \Phi^* D^\nu \Phi + D^\nu \Phi^* D^\mu \Phi - g^{\mu\nu} (D_\lambda \Phi^* D^\lambda \Phi - m^2 \Phi^* \Phi). \quad (13)$$

Note: although the improvement tensor  $\mathcal{K}^{\lambda\mu\nu}$  for the EM + matter system is the same as for the free EM fields, in presence of an electric current  $J^\mu$  its derivative  $\partial_\lambda \mathcal{K}^{\lambda\mu\nu}$  contains an extra  $J^\mu A^\nu$  term. Pay attention to this term — it is important for obtaining a gauge-invariant stress-energy tensor (13) for the scalar field.

(c) Use the scalar fields' equations of motion and the non-commutativity of covariant derivatives

$$[D_\mu, D_\nu]\Phi = iqF_{\mu\nu}\Phi, \quad [D_\mu, D_\nu]\Phi^* = -iqF_{\mu\nu}\Phi^* \quad (14)$$

to show that

$$\partial_\mu T_{\text{mat}}^{\mu\nu} = +F^{\nu\lambda}J_\lambda \quad (15)$$

exactly as in eq. (8), and therefore the *net* stress-energy tensor (12) is conserved, *cf.* problem 1(e).

3. Finally, consider the Noether currents of an internal rather than translational symmetry. Let  $\Phi^a(x)$  be  $N$  complex scalar fields — of similar masses and electric charges — which interact with each other and with the EM fields  $A^\mu$  according to the Lagrangian

$$\mathcal{L} = \sum_a D_\mu \Phi_a^* D^\mu \Phi^a - m^2 \sum_a \Phi_a^* \Phi^a - \frac{\lambda}{4} \left( \sum_a \Phi_a^* \Phi^a \right)^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}. \quad (16)$$

The  $D_\mu \Phi^a$  and the  $D_\mu \Phi_a^*$  here are as in eq. (10) — they are covariant derivatives WRT the local  $U(1)$  symmetry associated with the EM fields. Specifically, all the  $\Phi^a$  fields have the same electric charge  $+q$  while the complex-conjugate fields  $\Phi_a^*$  have charge  $-q$ .

Both the electric charges and the scalar potentials are invariant under global unitary “rotations” of the  $\Phi^a$  fields into each other. (But not into the conjugate  $\Phi_a^*$  fields with different electric charges.) Such symmetries act according to

$$\Phi^a(x) \rightarrow \sum_b U_b^a \times \Phi^b(x), \quad \Phi_a^*(x) \rightarrow \sum_b \Phi_b^*(x) \times (U^\dagger)_a^b, \quad A^\mu(x) \text{ unchanged}, \quad (17)$$

where  $U = \|U_b^a\|$  is any *unitary*  $N \times N$  matrix. The group of such matrices — and hence of symmetries (17) — is called the  $U(N)$ .

(a) Check that the Lagrangian (16) is invariant under any  $U(N)$  symmetry (17).

- (b) The infinitesimal  $U(N)$  symmetries have form  $U = 1 + i\epsilon T$  — *i.e.*,  $U_b^a = \delta_b^a + i\epsilon T_b^a$  — for *hermitian* matrices  $T$ .

Derive the Noether current  $J_T^\mu$  for any given hermitian matrix  $T$ , then show that all the independent currents form an hermitian matrix of currents

$$J_b^{\mu a} = i\Phi^a D^\mu \Phi_b^* - i\Phi_b^* D^\mu \Phi^a = (J_a^{\mu b})^*. \quad (18)$$

- (c) Verify the conservation of the currents (18).

The scalar potential in the Lagrangian (16) has a bigger symmetry than the  $U(N)$ , namely the  $SO(2N)$  which rotates the real and imaginary parts of the  $\Phi_a(x)$  fields as if they were  $2N$  unrelated real fields. But the  $SO(2N)$  symmetries outside of the  $U(N)$  do not commute with the local  $U(1)$  symmetry of the charged fields and hence do not preserve their couplings to the EM fields.

- (d) Work this out.

The infinitesimal form of an  $SO(2N)$  symmetry outside of the  $U(N)$  is

$$\delta\Phi^a(x) = \epsilon \sum_b C^{ab} \Phi_b^*(x), \quad \delta\Phi_a^*(x) = \epsilon \sum_b C_{ab}^* \Phi^b(x) \quad (19)$$

for a complex antisymmetric matrix  $C^{ab} = -C^{ba}$ .

- (e) Write down the Noether current for such a would-be symmetry and show that it is NOT conserved (unless  $A^\mu = 0$ ).