



## MTHS24 – Exercise sheet 4

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## Lecture material

### Discussed topics:

- Partial waves
- Analyticity
- Unitarity

### References:

- Book 1, [inspire](#)
- Book 2, [amazon](#)
- A good review, [inspire](#)
- A good aper, [inspire](#)

## Exercises

### 4.1 Field redefinition

Using the path integral formalism of quantum field theory, one notices that physical observables are independent of field redefinitions  $\phi \rightarrow \phi + f(\phi/\Lambda)$ , where  $\Lambda$  is a dimensionful parameter. This redefinition does not affect observables, because the integration in the generating functional  $Z[J]$  is done over all configurations of  $\phi$  and the measure  $\mathcal{D}\phi$  compensates any changes of variables due to the Jacobian. Note that one can drop the additional interpolating field in the part containing the external current  $J$  (and work just with  $J\phi$ ) without changing the S-matrix (though Green's functions do change!).

In this exercise we consider the free scalar theory for a field  $\phi$  and will demonstrate that the amplitude for  $\phi\phi \rightarrow \phi\phi$  scattering is not affected by the field redefinition

$$\phi \rightarrow \phi + \frac{\phi^2}{\Lambda}. \quad (1)$$

- Transform the Lagrangian for a free real scalar field  $\phi$  with mass  $m$  under the above field redefinition.
- By applying functional derivatives as summarized in appendix 4.5, show that the Feynman rules for

all of the four interaction parts are given as

$$= -\frac{12im^2}{\Lambda^2} \quad (2)$$

$$= -\frac{8i}{\Lambda^2} (p_1 \cdot p_2 + p_1 \cdot p_3 + p_1 \cdot p_4 + p_2 \cdot p_3 + p_2 \cdot p_4 + p_3 \cdot p_4) \quad (3)$$

$$= -\frac{6im^2}{\Lambda} \quad (4)$$

$$= -\frac{4i}{\Lambda} (p_1 \cdot p_2 + p_1 \cdot p_3 + p_2 \cdot p_3) \quad (5)$$

- (c) Show that the amplitude for  $\phi\phi \rightarrow \phi\phi$  (with incoming momenta  $p_1$  and  $p_2$  and outgoing momenta  $p_3$  and  $p_4$ ) is zero at tree level by explicit calculation.

*Hint:* For some of the tree diagrams you need to consider the  $s$ ,  $t$  and  $u$  channel, where  $s$ ,  $t$  and  $u$  are the Mandelstam variables. It follows from four-momentum conservation that  $s + t + u = 4m^2$ .

## 4.2 Linear sigma model

The linear sigma model is a toy model which illustrates the concept of spontaneous symmetry breaking and the appearance of Goldstone bosons. It is also used as a prototype for the chiral perturbation theory.

We will consider the following (classic) Lagrangian:

$$\mathcal{L} = \frac{1}{2} \partial_\mu \Phi_i \partial^\mu \Phi_i - \frac{1}{2} m^2 \Phi^2 - \frac{1}{4} \lambda (\Phi^2)^2, \quad (6)$$

consisting of four real scalar fields  $\Phi = (\Phi_1, \Phi_2, \Phi_3, \Phi_4)$ , with  $\lambda > 0$ .

This model has an  $SO(4)$  symmetry, while quantum chromodynamics with two massless quarks has an  $SU(2) \times SU(2)$  symmetry, corresponding to isospin rotations done separately on the left handed and right handed component of the quark fields. Because  $SO(4)$  is isomorphic to  $SU(2) \times SU(2)$ , the linear sigma model has the same symmetry group as the strong interaction (in the case of two massless quarks).

Now consider  $m^2 < 0$ , i.e.,  $-m^2 = \mu^2$  and convince yourself that the Lagrangian in Eq. (6) is equivalent to

$$\mathcal{L} = \frac{1}{2} \partial_\mu \Phi_i \partial^\mu \Phi_i - \underbrace{\frac{\lambda}{4} (\Phi^2 - v^2)^2}_{=: \mathcal{V}}, \quad \text{with } v = \frac{\mu}{\sqrt{\lambda}} > 0. \quad (7)$$

The minimum of the potential  $\mathcal{V}$  is then given by the equation  $\Phi^2 = v^2$ , which corresponds not to a single, but an infinite number of points. We choose one of them as our vacuum state:

$$\Phi = |0\rangle = (0, 0, 0, v). \quad (8)$$

The vacuum is not invariant under all  $\text{SO}(4)$  transformations. One can show that three of the  $\text{SO}(4)$  generators do not annihilate it. This is called *spontaneous symmetry breaking* (SSB) and, according to the *Goldstone theorem*, there should appear three massless bosons in such a system.

We can rewrite the Lagrangian in terms of the fields  $\sigma$  and  $\vec{\pi}$ , which are fluctuations around this vacuum:

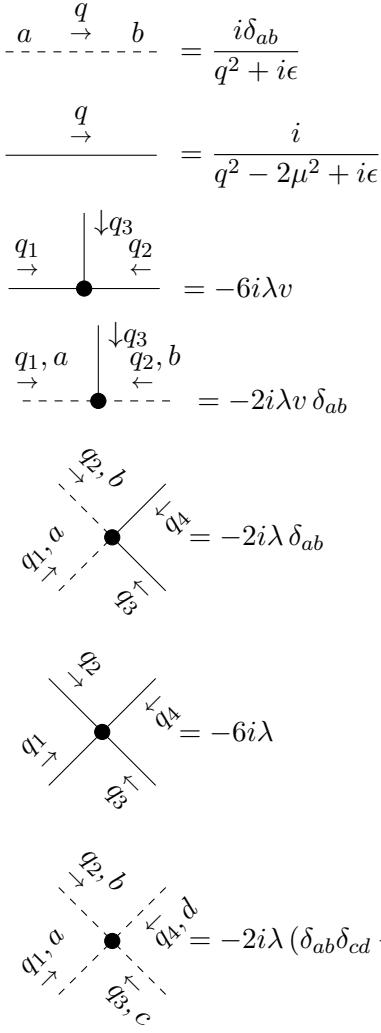
$$\Phi = (\Phi_1, \Phi_2, \Phi_3, \Phi_4) = (\pi_1, \pi_2, \pi_3, v + \sigma) = (\vec{\pi}, v + \sigma). \quad (9)$$

- (a) Show that in terms of the fields  $\sigma$  and  $\vec{\pi}$  the Lagrangian of Eq. (7) reads

$$\mathcal{L} = \frac{1}{2} \partial_\mu \pi_i \partial^\mu \pi_i + \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} (2\mu^2) \sigma^2 - \lambda v \sigma^3 - \lambda v \sigma \vec{\pi}^2 - \frac{\lambda}{2} \sigma^2 \vec{\pi}^2 - \frac{\lambda}{4} \sigma^4 - \frac{\lambda}{4} (\vec{\pi}^2)^2, \quad (10)$$

describing a theory of a massive  $\sigma$  field and three *massless*  $\pi$  fields, which we will call “pion fields”,<sup>1</sup> interacting through (five) different potential terms that all become small at  $\lambda \rightarrow 0$ .

- (b) Show that the Feynman Rules for the propagators and vertices are given as follows<sup>2</sup>:



- (c) Show that the pion fields remain massless when the one-loop corrections are included. Remember that the physical particle mass is obtained from the self-energy, in particular, for a pion with external momentum  $p$  as

$$m_\pi^2 = \Sigma_\pi(p^2 = m_\pi^2). \quad (11)$$

<sup>1</sup>We do this to emphasize the connection to pion particles, even if our  $\pi$ s are not describing physical pions.

<sup>2</sup>You can use one type of line for all pion fields at once (e.g., dashed in Fig. 1) and denote the different fields by indices at the lines. This yields a Kronecker delta  $\delta_{ij}$  as factor for the pion propagator (for particles  $\pi_i$  and  $\pi_j$  at the ends) as well as factors of certain Kronecker deltas for some vertices.

The leading diagrams contributing to  $\Sigma_\pi$  are shown in Fig. 1, where a dashed line denotes the pion field and a solid line denotes the sigma field. Write down their mathematical expressions and show that Eq. (11) holds true for  $m_\pi^2 = 0$ .

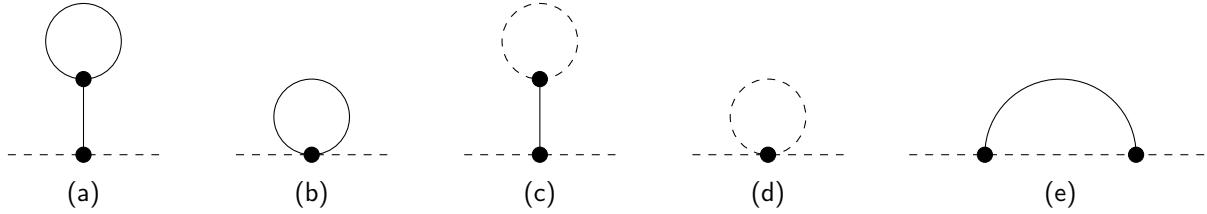


Figure 1: The leading order diagrams contributing to  $\Sigma_\pi$ .

*Hint 1:* The last diagram has a symmetry factor 1, all others have a symmetry factor 2. The mathematical expression of each diagram has to be divided by its symmetry factor.

*Hint 2:* How to treat the pion indices of pion loops?

*Hint 3:* You can write the result of any diagram  $n$  as  $\Sigma_n = \delta_{ij} X^n \times I_n$ , where  $X^n$  is some coefficient that contains the symmetry factor of diagram  $n$  and  $I_n$  contains only the one-loop part. Make sure that when the loop contains one propagator, then  $I_n$  can be either  $I_n = I^1 = \int \frac{d^d l}{(2\pi)^d} \frac{i}{l^2 - 2\mu^2 + i\epsilon}$  or  $I_n = I^2 = \int \frac{d^d l}{(2\pi)^d} \frac{i}{l^2 + i\epsilon}$  and for two propagators in the loop we have  $I_n = I^3 = \int \frac{d^d l}{(2\pi)^d} \frac{i}{(l-p)^2 + i\epsilon} \frac{i}{l^2 - 2\mu^2 + i\epsilon}$ , where because of  $m_\pi^2 = 0$  we have  $p^2 = 0$ .

*Hint 4:* You can keep the loop integrals without carrying out the momentum integration. But you should express  $I^3$  in terms of  $I^1$  and  $I^2$ . For that, you can use Feynman parametrization to show the independence of the angular part as follows:

$$\begin{aligned}
 \int d^d l \frac{1}{(l-p)^2 (l^2 - 2\mu^2)}|_{p^2=0} &= \int dx \int d^d l [x(p-l)^2 + (1-x)(l^2 - 2\mu^2)]|_{p^2=0} \\
 &= \int dx \int d^d l [(l-px)^2 - p^2 x^2 + xp^2 + (1-x)2\mu^2]|_{p^2=0} \\
 &\stackrel{l-px \rightarrow l}{=} \int dx \int d^d l [l^2 - p^2 x^2 + xp^2 + (1-x)2\mu^2]|_{p^2=0} \\
 &= \int dx \int d^d l [xl^2 + (1-x)(l^2 - 2\mu^2)] = \int d^d l \frac{1}{l^2(l^2 - 2\mu^2)}, 
 \end{aligned} \tag{12}$$

Now show that  $\frac{1}{l^2(l^2 - 2\mu^2)} = \frac{1}{2\mu^2} \left( \frac{1}{l^2 - 2\mu^2} - \frac{1}{l^2} \right)$ . Use your results and write the self-energy as  $\Sigma_a + \Sigma_b + \Sigma_c + \Sigma_d + \Sigma_e = \lambda \delta_{ij} (\alpha I^1 + \beta I^2)$ , where  $\alpha$  and  $\beta$  are expected to be zero.

*Remark:* That pions are massless even beyond the classical (tree level) calculation is a non-trivial characteristic and is due to the SSB, which “protects” the (zero) pion mass.

- (d) Compute the scattering amplitude for  $\pi_i(p_1)\pi_j(p_2) \rightarrow \pi_k(p_3)\pi_l(p_4)$  at tree level. Show that these diagrams sum up to zero at the threshold  $\vec{p}_i = \vec{0}$ .

*Remark:* It is a general feature that the interactions of Goldstone bosons vanish for low energies. This is the foundation for the construction of *Chiral Perturbation Theory*, where all pion interaction terms have to contain derivatives.

### 4.3 Compensator field for chiral transformations

The pion fields  $(\pi^0, \pi^+, \pi^-)$  are conveniently expressed in the chiral effective Lagrangian in terms of their cartesian components  $\pi^a \in \{\pi^1, \pi^2, \pi^3\}$  as follows:

$$\pi^0 = \pi^3, \pi^+ = \frac{1}{\sqrt{2}} (\pi^1 - i\pi^2), \pi^- = \frac{1}{\sqrt{2}} (\pi^1 + i\pi^2). \quad (13)$$

In the two-flavor sector the pion fields  $\pi^a$  appear in the Lagrangian via the matrix  $U = u^2$ , which can be parametrized as follows

$$U = \mathbf{1}_{2 \times 2} + i \frac{\boldsymbol{\tau} \cdot \boldsymbol{\pi}}{F} - \frac{\boldsymbol{\pi}^2}{2F^2} - i\alpha \frac{\boldsymbol{\pi}^2 \boldsymbol{\tau} \cdot \boldsymbol{\pi}}{F^3} + (8\alpha - 1) \frac{\boldsymbol{\pi}^4}{8F^2} + \mathcal{O}(\boldsymbol{\pi}^5), \quad (14)$$

where  $\alpha$  is an arbitrary constant which reflects the freedom in the parametrizing the matrix  $U$ ,  $\tau^a$  are the Pauli matrices and  $F$  is the pion decay constant in chiral limit.

The pionic matrix  $U$  transforms under chiral rotations as follows:

$$U \mapsto LUR^\dagger, \quad (15)$$

where  $R$  and  $L$  are spacetime-dependent  $SU(2)$  matrices. From the above equation, it follows that the matrix  $u$  transforms under chiral rotations as follows:

$$u \mapsto u' = \sqrt{LuR^\dagger} \equiv Luh^{-1} = huR^\dagger, \quad (16)$$

where the unitary matrix  $h = h(L, R, U) = \sqrt{LUR^\dagger}^{-1} L \sqrt{U}$  is sometimes referred to as a compensator field.

Calculate the explicit form of the compensator field  $h$  for infinitesimal chiral transformations using Eq. (14) and keeping only terms that are at most linear in the pion fields. Verify also that  $h$  indeed reduces to the isospin transformation for  $L = R = V$ .

### 4.4 Fermionic charges of isospin symmetry

We consider the isospin symmetry of nucleons, which is approximately realized in nature since proton and neutron have almost the same mass  $m_N$ . As for spin, the symmetry group is  $SU(2)$  with the Lie algebra  $\text{su}(2)$ , which has the Levi-Civita symbol  $\varepsilon_{abc}$  as structure constants and the isospin Pauli matrices

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \text{with } \vec{\tau} := (\tau_1, \tau_2, \tau_3) \quad (17)$$

divided by 2 as basis (or generators) of the fundamental representation, i.e., they fulfill the equation

$$\left[ \frac{\tau_i}{2}, \frac{\tau_j}{2} \right] = i\varepsilon_{ijk} \frac{\tau_k}{2}. \quad (18)$$

Consider the free fermion Lagrangian

$$\mathcal{L} = \bar{\Psi} (i\cancel{\partial} - m_N) \Psi, \quad (19)$$

where the two-component field vector  $\Psi := (p, n)^T$  is build of the proton field  $p$  and neutron field  $n$  which themselves are Dirac spinors, such that  $\Psi$  has two indices. It transforms under isospin via the fundamental representation as follows:

$$\Psi(x) \rightarrow \Psi'(x) = \Psi(x) + i\epsilon^i \frac{\tau_i}{2} \Psi(x) = \Psi(x) + i\vec{\epsilon} \cdot \frac{\vec{\tau}}{2} \Psi(x). \quad (20)$$

The (components of the) fermion field operators  $\Psi$  must obey the anticommutation relations

$$\{\Psi_{r,\alpha}(t, \vec{x}), \Psi_{s,\beta}^\dagger(t, \vec{y})\} = \delta^3(\vec{x} - \vec{y}) \delta_{rs} \delta_{\alpha\beta}, \quad \{\Psi_{r,\alpha}(t, \vec{x}), \Psi_{s,\beta}(t, \vec{y})\} = 0 = \{\Psi_{r,\alpha}^\dagger(t, \vec{x}), \Psi_{s,\beta}^\dagger(t, \vec{y})\}, \quad (21)$$

where  $r, s \in \{1, 2\}$  denote isospin indices and  $\alpha, \beta \in \{1, 2, 3, 4\}$  denote Dirac indices. We want to show that the  $\text{su}(2)$  charge operators<sup>3</sup> Appendix 4.5 contains a discussion that shows how to obtain the charges w.r.t.  $\mathcal{L}$  form a Hilbert space representation of the Lie algebra, i.e.,

$$[Q_i(t), Q_j(t)] = i\varepsilon_{ijk}Q_k(t). \quad (22)$$

We want to explicitly prove this in the following.

(a) Find the three charges as

$$\vec{Q}(t) = \int d^3x \Psi^\dagger(t, \vec{x}) \frac{\vec{\gamma}}{2} \Psi(t, \vec{x}). \quad (23)$$

(b) Show Eq. (22).

*Hint:* First verify  $[AB, CD] = A\{B, C\}D - AC\{B, D\} + \{A, C\}DB - C\{A, D\}B$ . Note that to apply this, the fields  $\Psi, \bar{\Psi}$  must be written in components.

## 4.5 Effective Lagrangian and heavy-baryon reduction of the free Dirac Lagrangian

(a) A quantum field theory for two scalar fields interacting with a Yukawa-like coupling, as considered in the lecture, is given by the Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 + \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi - \frac{1}{2}M^2\Phi^2 - \frac{\lambda}{2}\phi^2\Phi. \quad (24)$$

Assuming that  $\phi$  and  $\Phi$  correspond to a light and a heavy particle with masses  $m \ll M$ , one can derive an effective Lagrangian that involves only the light degrees of freedom. For processes on tree diagram level (i.e. on the classical level), this can be easily done by using the equation of motion (EOM).

Derive the EOM for the heavy field and show that it is formally solved by

$$\Phi = \frac{\lambda}{2 - \square - M^2}\phi^2, \quad (25)$$

where we use the D'Alembert operator  $\square = \partial_\mu\partial^\mu$ . Plug this solution back into the full Lagrangian and show that the Lagrangian can be written as follows<sup>4</sup>

$$\mathcal{L} = \mathcal{L}_0^\phi + \frac{1}{2}\left(\frac{\lambda}{2 - \square - M^2}\phi^2\right)(-\square - M^2)\left(\frac{\lambda}{2 - \square - M^2}\phi^2\right) - \frac{\lambda}{2}\phi^2\left(\frac{\lambda}{2 - \square - M^2}\phi^2\right) \quad (26)$$

$$= \mathcal{L}_0^\phi - \frac{\lambda^2}{8}\phi^2\frac{1}{-\square - M^2}\phi^2 \quad (27)$$

$$= \mathcal{L}_0^\phi + \frac{\lambda^2}{8}\frac{1}{M^2}\phi^2\frac{1}{1 + \frac{\square}{M^2}}\phi^2. \quad (28)$$

Using the following expansion

$$\left(1 + \frac{\square}{M^2}\right)^{-1} = 1 - \frac{\square}{M^2} + \left(\frac{\square}{M^2}\right)^2 + \left(\frac{1}{M^6}\right) \quad (29)$$

show that the effective Lagrangian up to and including order  $(1/M)^4$  can be written as<sup>5</sup>

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 + \frac{\lambda^2}{8}\frac{1}{M^2}\phi^4 - \frac{\lambda^2}{8}\frac{1}{M^4}\phi^2\square\phi^2 + \left(\frac{1}{M^6}\right). \quad (30)$$

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<sup>3\*</sup>

<sup>4</sup>You should transform and simplify the effective Lagrangian such that it is only expressed in multiples of  $\phi$ ,  $(\partial_\mu\phi)$  and  $(\partial^\mu\phi)$  (and is especially free from expressions like  $\partial_\mu(\phi^2)$  or  $\partial_\mu\partial^\mu\phi$ ).

<sup>5</sup>Note that you can do integration by parts in the Lagrangian, without changing physics, because there appears an integral in the action  $S = \int d^4x \mathcal{L}$  and the field are expected to vanish for large  $x$ .

(b) As next, consider the free Dirac Lagrangian given by

$$\mathcal{L} = \bar{\Psi} (i\cancel{d} - m) \Psi . \quad (31)$$

The nucleon mass is not expected to vanish in the chiral limit and it is not small compared to the chiral symmetry-breaking scale, thus complicating the expansion in powers of momenta by breaking the power counting of chiral perturbation theory. One way to solve this problem is the construction of heavy-baryon chiral perturbation theory (HBChPT), where the starting idea is to separate the nucleon four-momenta  $p$  into a large part close to the on-shell kinematics and a soft part  $k_p$ , as

$$p^\mu = mv^\mu + k_p^\mu, \quad \text{where } v \cdot v = 1, v^0 \geq 1 . \quad (32)$$

The relativistic nucleon field is then decomposed into a large and a small component

$$\Psi = e^{-imv \cdot x} [N_v(x) + H_v(x)] , \quad (33)$$

$$N_v(x) = e^{imv \cdot x} P_{v+} \Psi , \quad (34)$$

$$H_v(x) = e^{imv \cdot x} P_{v-} \Psi , \quad (35)$$

using the projection operators

$$P_{v\pm} = \frac{\mathbb{1} \pm \gamma}{2} . \quad (36)$$

You can convince yourself that they fulfill

$$P_{v+} + P_{v-} = \mathbb{1} , \quad P_{v\pm}^2 = P_{v\pm} , \quad P_{v\pm} P_{v\mp} = 0 . \quad (37)$$

Show that the free Dirac Lagrangian can be rewritten as follows:

$$\begin{aligned} \mathcal{L} &= \bar{N}_v(x) (iv \cdot \partial) N_v(x) - \bar{H}_v(x) (iv \cdot \partial + 2m) H_v(x) + \bar{N}_v(x) (i\cancel{d}_\perp) H_v(x) \\ &+ \bar{H}_v(x) (i\cancel{d}_\perp) N_v(x) , \end{aligned} \quad (38)$$

where  $\partial_\perp \equiv \partial - (v \cdot \partial)v$ .

Proceed now similarly to the case of scalar fields in (a) and derive the EOM for the field  $\bar{H}_v(x)$  and plug the solution back into the full Lagrangian in Eq. (38) and expand in powers of  $1/m$  to derive the effective Lagrangian up to and including the next-to-leading order in  $1/m$ .

## Appendix: Functional derivatives

Functions take elements of an arbitrary set and map it to exactly one element of another set, e.g.,  $f: \mathbb{R}^n \rightarrow \mathbb{R}^m$ . Functionals take elements from function spaces, such as  $L^2(\mathbb{R}^n)$  or  $C^n(\mathbb{R}^m)$ , and map them to the complex or real numbers. Two examples are the integral with the Dirac delta function or the norm on  $L^2(\mathbb{R}^n)$ ; in this case we have  $F: L^2(\mathbb{R}^n) \rightarrow \mathbb{R}$ .

In physics the most common example is the action functional  $S[x]$ . Closely connected to the action is the *variational principle*, which derives the equation of motion from the action. To explain this, consider a functional  $F[\phi]$  and assume that an arbitrary small variation  $\phi(x) \rightarrow \phi(x) + \epsilon h(x)$  is performed. Mathematically, this describes the rate of change of  $F[\phi]$  when  $\phi$  is perturbed at the point  $x$  and is calculated by taking the *functional derivative*.

The functional derivative is defined similarly to the ordinary derivative:

$$\int d^4z \frac{\delta F[\phi]}{\delta \phi(z)} h(z) = \lim_{\epsilon \rightarrow 0} \frac{F[\phi + \epsilon h] - F[\phi]}{\epsilon} , \quad (39)$$

where  $h$  is an arbitrary test function and the limit  $\varepsilon \rightarrow 0$  is to be taken before any integration.

Note that the definition above corresponds to the directional derivative, here in the direction of  $h$  and by using the Dirac delta function  $h(z) = \delta(z - x)$  the left hand side of the equation simplifies to  $\frac{\delta F[\phi]}{\delta\phi(x)}$ .

Using the definition it can be shown, similar to the proofs in for the classical derivative, that the functional derivative is linear and follows the product rule:

$$\frac{\delta(\alpha F + \beta G)[\phi]}{\delta\phi(x)} = \alpha \frac{\delta F[\phi]}{\delta\phi(x)} + \beta \frac{\delta G[\phi]}{\delta\phi(x)}, \quad (40)$$

$$\frac{\delta(FG)[\phi]}{\delta\phi(x)} = \frac{\delta F[\phi]}{\delta\phi(x)} G[\phi] + F[\phi] \frac{\delta G[\phi]}{\delta\phi(x)}. \quad (41)$$

Because the functional derivative fulfills these two properties, it is also a derivative in the strict mathematical sense. Many other properties of functional derivatives are the same as for ordinary derivatives, like the chain rule.

Several simple examples of functional derivatives are given in the following list:

$$(a) \frac{\delta\phi(x)}{\delta\phi(y)} = \delta^4(x - y)$$

$$(b) \frac{\delta}{\delta\phi(y)} \int d^4x \phi(x) g(x) = g(y)$$

$$(c) \frac{\delta}{\delta\phi(y)} \int d^4x (\phi(x))^n = n(\phi(y))^{n-1}$$

$$(d) \frac{\delta}{\delta\phi(z)} \exp \left( \int d^4x \phi(x) J(x) \right) = J(z) \exp \left( \int d^4x \phi(x) J(x) \right)$$

(The exponential function is understood as its corresponding power series here.)

## Appendix: Noether's theorem

**Definition:** Given a set of fields  $\phi_i$  (to be understood as scalar fields or components of vector fields), an infinitesimal global transformation

$$\begin{aligned} x^\mu &\rightarrow x'^\mu = f^\mu(x, \epsilon) = x^\mu + \epsilon^a A_a^\mu(x), \quad \phi_i(x) \rightarrow \phi'_i(x') = \phi_i(x) + \epsilon^a F_{i,a}(\phi(x)) \\ \Rightarrow \phi'_i(x) &= \phi_i(x) + \underbrace{(F_{i,a}(\phi(x)) - A_a^\mu(x) \partial_\mu \phi_i(x))}_=: \Delta_{i,a} \epsilon^a \equiv \phi_i(x) + \delta\phi_i(x), \end{aligned} \quad (42)$$

with the parameters  $\epsilon^a$  ( $a = 1, \dots, N$ ) is called a *symmetry* if it leaves invariant the action

$$S = \int_{\Omega} d^4x \mathcal{L}(\phi(x), \partial_\mu \phi(x)), \quad \text{i.e.,} \quad S = S' = \int_{\Omega' = f(\Omega, \epsilon)} d^4x' \mathcal{L}(\phi'(x'), \partial' \phi'(x')). \quad (43)$$

**Theorem:** For each symmetry with corresponding transformation (42) and  $\phi_i$  satisfying the classical equations of motion (EOMs)

$$\frac{\partial \mathcal{L}}{\partial \phi_i} - \partial_\mu \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi_i)} = 0, \quad (44)$$

there exist  $N$  conserved *Noether currents*

$$j_a^\mu = - \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi_i)} \Delta_{i,a} - A_a^\mu \mathcal{L} \quad \text{which fulfill} \quad \partial_\mu j_a^\mu(x) = 0. \quad (45)$$

As a direct implication, one obtains the conserved *Noether charges*

$$Q_a = \int_{\mathbb{R}^3} d^3x j_a^0(x) \quad \text{with} \quad \frac{d}{dt} Q_a = 0. \quad (46)$$

## Appendix: Method of Gell-Mann and Lévy

The above definition is written for a *global* symmetry where the transformation parameters  $\epsilon^a$  are constant. For calculating a Noether current, it may however be useful to promote this global symmetry to a *local* symmetry, i.e., to assume that  $\epsilon^a$  are functions of space-time:  $\epsilon^a \rightarrow \epsilon^a(x)$ . Using the EOMs, one can show that the current and its divergence are then obtainable from

$$j_a^\mu = -\frac{\partial(\Delta\mathcal{L})}{\partial(\partial_\mu\epsilon_a)} \quad \text{and} \quad \partial_\mu j_a^\mu = -\frac{\partial(\Delta\mathcal{L})}{\partial\epsilon_a}, \quad (47)$$

with the action difference  $\int_\Omega d^4x \Delta\mathcal{L} = \int_{\Omega'} d^4x' \mathcal{L}(\phi'(x'), \partial'\phi'(x')) - \int_\Omega d^4x \mathcal{L}(\phi(x), \partial\phi(x))$  given by

$$\int_\Omega d^4x \Delta\mathcal{L} = \int_\Omega d^4x \left( \partial_\mu(\epsilon^a(x) A_a^\mu(x) \mathcal{L}(\phi(x), \partial\phi(x))) + \frac{\partial\mathcal{L}}{\partial\phi_i} \delta\phi_i(x) + \frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi_i)} \delta(\partial_\mu\phi_i(x)) \right) \quad \forall \Omega. \quad (48)$$

Requiring the stronger symmetry constraint  $\Omega' = \Omega$ , the symmetry condition  $S = S'$  of Eq. (43) becomes  $d^4x \mathcal{L}(\phi(x), \partial\phi(x)) = d^4x' \mathcal{L}(\phi'(x'), \partial'\phi'(x'))$ . If further  $d^4x = d^4x'$ , the symmetry condition is equivalent to the invariance of the Lagrangian:  $\mathcal{L}(\phi(x), \partial\phi(x)) = \mathcal{L}(\phi'(x'), \partial'\phi'(x'))$ .

In particular, this is fulfilled if the coordinates themselves are invariant, i.e.,  $x^\mu \rightarrow x^\mu$  or  $A_a^\mu = 0$ . In this case, the Noether current (45) simplifies to  $j_a^\mu = -\frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi_i)} F_{i,a}$  and  $\Delta\mathcal{L}$  reduces to the Lagrangian variation

$$\delta\mathcal{L} = \frac{\partial\mathcal{L}}{\partial\phi_i} \delta\phi_i + \frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi_i)} \partial_\mu \delta\phi_i, \quad \text{so that Eq. (47) becomes} \quad j_a^\mu = -\frac{\partial(\delta\mathcal{L})}{\partial(\partial_\mu\epsilon_a)}, \quad \partial_\mu j_a^\mu = -\frac{\partial(\delta\mathcal{L})}{\partial\epsilon_a}, \quad (49)$$

which in this form can be a very convenient tool, because  $\delta\mathcal{L}$  can be easily computed for a given transformation. Moreover, the method also works for “non-conserved currents”  $\partial_\mu j_a^\mu \neq 0 \neq \delta\mathcal{L}$ , i.e., if the transformation is not a symmetry.