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RENORMALIZATION GROUP EQUATIONS IN DIFFERENT APPROACHES

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RENORMALIZATION GROUP EQUATIONS IN DIFFERENT APPROACHES

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I. Introduction

Different renormalization approaches are used in quantum field theory for the perturbation theory calculations. All these approaches are certainly equivalent, providing the same values of the observable quantities. However at the intermediate stage of the calculations a certain dependence on the renormalization scheme does exist, in particular, in the case of renormalization group functions (anomalous dimensions and Gell-Mann-Low functions). It is of interest to find out the explicit form of this dependence and derive the relations, connecting the parameters of renormalization group equations in different schemes.

This is made in Secs. II and III of the present paper. Then, in Sec. IV the advantages of the renormalization scheme proposed by 't Hooft /1/ is briefly discussed and the most convenient way to perform the renormalization group calculations is pointed out.

It should be noted that only the asymptotic form of renormalization group equations is of interest in this paper, so that all masses can be put equal to zero from the very beginning. The legitimacy of this step is not obvious even for all momenta tending to infinity /2/. However the calculations in any given order of perturbation theory cannot forbid it, while there exists an example (asymptotically free theories) where this step is justified. So that one can expect the relations derived below are applicable to a sufficiently large class of theories.

I am grateful to D.V. Shirkov for interest in this work and stimulating criticism.

II. Renormalization group equations for non-normalized Green functions and invariant charges.

In this section we consider the Green functions $\Gamma\left(\frac{K^2}{\mu^2}, g\right)$ calculated with all masses put equal to zero and normalized by the condition $\Gamma\left(\frac{K^2}{\mu^2}, 0\right)=1$ when the radiative corrections are absent. All independent momentum arguments of Γ are assumed to be proportional to K^2 with the coefficients implicitly included into the definition of Γ. The dimensional parameter μ^2 characterizes the subtraction procedure. We shall call the renormalization scheme the λ-scheme, if the condition

$$\Gamma(1, g)=1 \tag{1}$$

is obeyed. In this case the function Γ is written as $\Gamma\left(\frac{K^2}{\lambda^2}, g\right)$, since the parameter μ^2 is here identical with the subtraction point λ^2. If the Green functions are not normalized and $\Gamma(1,g)= =p(g)\neq 1$ then it will be the μ-scheme. The following schemes belong to this class: i) 't Hooft's renormalization approach, here μ being the "unit of mass"; ii) the Feynman cut-off, where μ^2 is Λ^2 or, for instance, iii) the following subtraction procedure: the subtraction points λ_i^2 are proportional to λ^2, $\lambda_i^2=a_i\lambda^2$; the external momenta K_i^2 equal $b_i K^2$, but $a_i\neq b_i$.

Consider the derivation of renormalization group equations in the μ-scheme. All required relations can be obtained from the condition of the multiplicative renormalization of Green functions:

$$\Gamma\left(\frac{K^2}{\mu^2}, g\right)=Z\left(\frac{\mu'^2}{\mu^2}, g, g'\right)\Gamma\left(\frac{K^2}{\mu'^2}, g'\right). \tag{2}$$

In the case of invariant charges we have

$$\bar{g}\left(\frac{\kappa^2}{\mu^2}, g\right) = \bar{g}\left(\frac{\kappa^2}{\mu'^2}, g'\right).$$

The normalization condition is $\bar{g}(1, g) = q(g)$, where $q(g) = g$ only in the λ-scheme. We find from (2)

$$q(g') = \bar{g}\left(\frac{\mu'^2}{\mu^2}, g\right), \quad g' = q^{-1}\left(\bar{g}\left(\frac{\mu'^2}{\mu^2}, g\right)\right).$$

Using the notation $x = \frac{\kappa^2}{\mu^2}$, $t = \frac{\mu'^2}{\mu^2}$ we obtain the functional equation of renormalization group

$$\bar{g}(x, g) = \bar{g}\left(\frac{x}{t}, q^{-1}\left(\bar{g}(t, g)\right)\right). \tag{3}$$

Differentiating eq. (3) with respect to t and then putting $t = 1$ results in the differential equation of Ovsiannikov type [3,4,5]

$$\left(x\frac{\partial}{\partial x} - \beta(g)\frac{\partial}{\partial g}\right)\bar{g}(x, g) = 0, \tag{4}$$

where $$\beta(g)\frac{dq(g)}{dg} = \varphi(g) = \frac{\partial \bar{g}(x, g)}{\partial x}\Big|_{x=1}.$$

It is easy to show that $\beta(g) = \frac{\partial g}{\partial \ln \mu^2}\Big/\bar{g}$ fixed. Consequently the Gell-Mann-Low function $\beta(g)$ determines the change of g under renormalization group transformations.

Differentiating eq.(3) with respect to x and putting then $t = x$ yields the differential equation in the Lie form [4,5]

$$x\frac{\partial}{\partial x}\bar{g}(x, g) = f\left(\bar{g}(x, g)\right), \tag{5}$$

where $f(q(g)) = \varphi(g)$. On account of the normalization condition on $\bar{g}$ the eqs.(4) and (5) are equivalent. However the functions β and f are identical only in the λ-scheme. Otherwise we can expand both sides of the equality

$$f(q(g)) = \beta(g)\frac{dq(g)}{dg} \tag{6}$$

in powers of g and find that two first terms of β and f coincide while the higher terms are generally different. Indeed, it is easy to realize that an expansion of β and f begins with the order of g^2 while that of q begins with the order of g.

Thus
$$\beta(g) = ag^2 + bg^3 + cg^4 + \dots \quad ,$$
$$f(g) = \bar{a}g^2 + \bar{b}g^3 + \bar{c}g^4 + \dots \quad ,$$
$$q(g) = g + Ag^2 + Bg^3 + \dots \quad .$$

Then eq.(6) to g^4-order looks as follows
$$\bar{a}\left(g^2 + 2Ag^3 + 2Bg^4 + A^2g^4\right) + \bar{b}\left(g^3 + 3Ag^4\right) + \bar{c}g^4 =$$
$$= ag^2 + (2Aa + b)g^3 + (2Ab + 3aB + c)g^4 .$$

Hence it immediately follows that
$$a = \bar{a} \ , \quad b = \bar{b} \ , \quad c = \bar{c} + aA^2 + aB - bA .$$

So one can observe that in a single-charge theory a certain cancellation takes place in the two-loop approximation, which results in $b = \bar{b}$. The cancellations of such a type have been first indicated in paper /6/. Note that one can reconstruct f out of β in any given order of perturbation theory using the function $q(g)$ calculated up to a previous order.

It appears to be convenient to introduce an "effective coupling constant" /2/ $\xi(x,g) = q^{-1}(\bar{g}(x,g))$, which obeys the normalization condition $\xi(1,g) = g$ and the equations of the Lie and Ovsiannikov types

$$\left(x\frac{\partial}{\partial x} - \beta(g)\frac{\partial}{\partial g}\right)\xi(x,g) = 0 \quad , \quad x\frac{\partial}{\partial x}\xi(x,g) = \beta(\xi(x,g)) .$$

Recall the relation (2) for Green's functions $\Gamma(x,g)$. We use the normalization condition $\Gamma(1,g) = p(g)$ to obtain the functional equation for $\Gamma(x,g)$

$$\Gamma(x,g)\,p(\xi(t,g)) = \Gamma(t,g)\,\Gamma\left(\frac{x}{t},\xi(t,g)\right). \qquad (7)$$

Similarly to a previous case differentiating eq.(7) with respect to t and then putting $t=1$ yields the Ovsiannikov equation

$$\left(x\frac{\partial}{\partial x} - \beta(g)\frac{\partial}{\partial g} + \gamma_\Gamma(g)\right)\Gamma(x,g) = 0 \ , \qquad (8)$$

where

$$\gamma_\Gamma(g) = \beta(g)\frac{d\ln p(g)}{dg} + \overline{\Psi}_\Gamma(g) \ , \quad \overline{\Psi}_\Gamma(g) = -\left.\frac{\partial \ln \Gamma(x,g)}{\partial x}\right|_{x=1}.$$

The Lie equation here reads

$$x\frac{\partial}{\partial x}\ln\Gamma(x,g) = -\Psi_\Gamma(\bar{g}(x,g)) \ , \qquad (9)$$

where

$$\Psi_\Gamma(q(g)) = \overline{\Psi}_\Gamma(g) = \gamma_\Gamma(g) - \beta(g)\frac{d\ln p(g)}{dg}. \qquad (10)$$

However a more convenient form of the Lie equation is

$$x\frac{\partial}{\partial x}\ln\Gamma(x,g) = -\overline{\Psi}_\Gamma(\xi(x,g)). \qquad (9a)$$

From eq.(10) one readily realizes that the functions γ_Γ, Ψ_Γ and $\overline{\Psi}_\Gamma$ coincide in the λ-scheme and are different in the μ-scheme beginning from the two-loop level. Now let us generalize the above results to the multi-charge case, taking the theory with two coupling constants as an example. Let the invariant charges $\bar{g}(x,g,h)$ and $\bar{h}(x,g,h)$ be normalized by $\bar{g}(1,g,h) = q_g(g,h)$, $\bar{h}(1,g,h) = q_h(g,h)$. Then the relations

$$\bar{g}(x,g,h) = q_g(\xi_g(x,g,h),\ \xi_h(x,g,h)) \ ,$$

$$\bar{h}(x,g,h) = q_h(\xi_g(x,g,h),\ \xi_h(x,g,h))$$

determine normalized functions $\xi_g(x,g,h)$ and $\xi_h(x,g,h)$

$$\xi_g(1,g,h) = g \ , \quad \xi_h(1,g,h) = h \ .$$

The invariant charges $\bar{g}$ and $\bar{h}$ satisfy the Ovsiannikov equations

$$\left(x\frac{\partial}{\partial x}-\beta_g(g,h)\frac{\partial}{\partial g}-\beta_h(g,h)\frac{\partial}{\partial h}\right)\left[\begin{matrix}\bar{g}(x,g,h)\\ \bar{h}(x,g,h)\end{matrix}\right]=0 \qquad (11)$$

and the Lie equations

$$x\frac{\partial}{\partial x}\,\bar{g}(x,g,h)=F_g\left(\bar{g}(x,g,h),\,\bar{h}(x,g,h)\right),$$

$$x\frac{\partial}{\partial x}\,\bar{h}(x,g,h)=F_h\left(\bar{g}(x,g,h),\,\bar{h}(x,g,h)\right), \qquad (12)$$

where

$$\frac{\partial q_g(g,h)}{\partial g}\beta_g(g,h)+\frac{\partial q_g(g,h)}{\partial h}\beta_h(g,h)=\frac{\partial \bar{g}(x,g,h)}{\partial x}\Big|_{x=1},$$

$$\frac{\partial q_h(g,h)}{\partial g}\beta_g(g,h)+\frac{\partial q_h(g,h)}{\partial h}\beta_h(g,h)=\frac{\partial \bar{h}(x,g,h)}{\partial x}\Big|_{x=1}.$$

The functions F and β are related by

$$F_g\left(q_g(g,h),\,q_h(g,h)\right)=\frac{\partial q_g(g,h)}{\partial g}\beta_g(g,h)+\frac{\partial q_g(g,h)}{\partial h}\beta_h(g,h),$$

$$F_h\left(q_g(g,h),\,q_h(g,h)\right)=\frac{\partial q_h(g,h)}{\partial g}\beta_g(g,h)+\frac{\partial q_h(g,h)}{\partial h}\beta_h(g,h). \qquad (13)$$

The functions ξ_g and ξ_h satisfy the equation (11) while in eq.(12) for these functions one must replace F_g, F_h by β_g, β_h. Let us write now the two-charge equations for a certain Green function $\Gamma(x,g,h)$ normalized by $\Gamma(1,g,h)=\rho(g,h)$. The Ovsiannikov equation reads

$$\left(x\frac{\partial}{\partial x}-\beta_g(g,h)\frac{\partial}{\partial g}-\beta_h(g,h)\frac{\partial}{\partial h}+\gamma_\Gamma(g,h)\right)\Gamma(x,g,h)=0. \qquad (14)$$

The Lie equation may be written in two different forms,

$$x\frac{\partial}{\partial x}\ln\Gamma(x,g,h)=-\,\Psi_\Gamma\left(\bar{g}(x,g,h),\,\bar{h}(x,g,h)\right), \qquad (15)$$

$$x\frac{\partial}{\partial x}\ln\Gamma(x,g,h)=-\,\bar{\Psi}_\Gamma\left(\xi_g(x,g,h),\,\xi_h(x,g,h)\right), \qquad (15a)$$

where $\bar{\Psi}_\Gamma(g,h)=-\frac{\partial}{\partial x}\ln\Gamma(x,g,h)\Big|_{x=1}$ and

$$\Psi_\Gamma\left(q_g(g,h),\, q_h(g,h)\right) = \overline{\Psi}_\Gamma(g,h) =$$
$$= \gamma_\Gamma(g,h) - \beta_g(g,h)\frac{\partial \ln p(g,h)}{\partial g} - \beta_h(g,h)\frac{\partial \ln p(g,h)}{\partial h}. \qquad (16)$$

III. Comparison of different renormalization schemes.

So far, we have dealt only with the Green functions of the same renormalization scheme. We shall now investigate the connection between the different approaches. Namely let us compare the λ-scheme with some μ-scheme.

Making the re-subtractions at the point λ^2 in the Green function $\Gamma\left(\frac{K^2}{\mu^2}, g\right)$, according to the R-operation, we obtain, through the finite renormalization, the Green function of λ-scheme, $\Gamma_\lambda\left(\frac{K^2}{\lambda^2}, g\right)$. The subscript λ emphasizes the difference between the functional forms of Γ and Γ_λ in addition to the change of their first arguments. Consequently,

$$\Gamma\left(\frac{K^2}{\mu^2}, g\right) = Z\,\Gamma_\lambda\left(\frac{K^2}{\lambda^2}, g'\right),$$

where g' and Z can be expressed uniquely in terms of g, μ^2 and λ^2. For the invariant charge we have

$$\overline{g}\left(\frac{K^2}{\mu^2}, g\right) = \overline{g}_\lambda\left(\frac{K^2}{\lambda^2}, g'\right).$$

The connection between the functions of two schemes is explicitly given by

$$\overline{g}(x,g) = \overline{g}_\lambda(x, q(g)), \quad \Gamma(x,g) = p(g)\,\Gamma_\lambda(x, q(g)).$$

Now one can write down the Lie equations in both schemes and see that they are identical, i.e., the functions f and Ψ_Γ do not vary from one scheme to another. This is valid for the multi-charge case as well. Taking into account the coincidence of β and f (as well as of γ_Γ and Ψ_Γ) in the λ-scheme we can call the formulas of the type (8), (10) "conversion formulas". These formulas connect the renormalization group functions of the Ovsiannikov equation obtained with the use of different renormalization prescriptions. Note in this connection that the form (9a) of Lie equation has the advantage of excluding the normalization function $q(g)$ from the definition of $\overline{\Psi}_r(g)$. Therefore the momentum dependence of the invariant charge $\bar{g}$ is of no importance for studying the asymptotic behaviour of the given Green function. It should be noted that $\xi(x,g)$ varies from one scheme to another, so that although being the normalized function, it does not coincide with the normalized invariant charge of the λ-scheme. Hence the function $\overline{\Psi}_r(g)$ depends on the renormalization prescriptions used, while $\Psi_r(g)$ does not. However the calculation of the latter function is more complicated.

Apart from the conversion formulas presented above one can obtain the relations between two different μ-schemes, for instance between 't Hooft's scheme and the Λ^2-cut-off method. Some of these formulas are given below:

$$\beta_\mu(g^*)\frac{dq_\mu(g^*)}{dg^*}=\beta_\Lambda(g)\frac{dq_\Lambda(g)}{dg}\;,\quad \overline{\Psi}_\mu(g^*)=\overline{\Psi}_\Lambda(g)\,,$$

$$\gamma_\mu(g^*)-\beta_\mu(g^*)\frac{d\ln p_\mu(g^*)}{dg^*}=\gamma_\Lambda(g)-\beta_\Lambda(g)\frac{d\ln p_\Lambda(g)}{dg}\;,$$

where g^* is to be determined from $q_\mu(g^*)=q_\Lambda(g)$. Analogous relations are established in paper /7/.

The formulas of such a type may be applied also to the asymptotic form of the Callan-Symanzik equations /8/. These equations are independent of renormalization group equations /9/ and belong to the class of μ-schemes. At first sight there is no distinction between the asymptotic Callan-Symanzik equations and the Ovsiannikov ones. But it should not be forgotten that these two kinds of equations are satisfied by the different Green functions. Indeed, in the Callan-Symanzik approach we do not use the dimensional parameter such as 't Hooft's "unit of mass" μ or the subtraction point λ^2, so that an argument x here means $\frac{k^2}{m^2}$. The asymptotic form of the Callan-Symanzik equations is associated with $|k^2| \gg m^2$. The corresponding conversion formula of type (6) was derived by Adler /10/. However in 't Hooft's scheme there exist no equations which are independent of renormalization group ones so, in fact, the Callan-Symanzik equations become an identity.

Using the described technique one can derive the conversion formulas for any given theory. In the prese... of gauge fields we must renormalize all gauge parameters as well. It results in the occurence of new equations with extra renormalization group functions. Clearly one can try to employ the conversion formulas to remove the discrepancies in many-loop calculatione in the different papers.

The calculations carried out in /11/ may be regarded as an illustration of such a case. In that paper the model φ^3 in six dimensions was treated and the two-loop expression of the remormalizations of propagators was obtained both in 't Hooft's and in λ--scheme. Using the conversion formula (10) one can easily check the consistency of these results.

The following fact should be noted. In the λ-scheme the subtraction point λ^2 depends on the ratios of external momenta. It is a direct consequence of normalizability of the invariant charges and the Green functions. Hence the β -functions of the λ -scheme and the f -function of the Lie equation in all renormalization schemes have also such a dependence. Conversely, 't Hooft's "unit of mass" μ and Feynman cut-off Λ^2 have no dependence on the ratios of external momenta. Therefore such a dependence does not enter into the Ovsiannikov equations in these schemes so that their renormalization group functions are simpler to evaluate than the functions of the universal Lie equation.

IV. General prescription for carrying out the renormalization group computations.

In the above sections we have obtained the conversion formulas which connect different renormalization approaches. One of the important properties of these formulas is that we need only the lower-order information on the normalization functions to reconstruct a certain renormalization group function in any given order of perturbation theory. Therefore when beginning the calculations in the next order we can use the most convenient method, namely 't Hooft's scheme, that is due to its numerous remarkable features. Among these there is, first of all, an explicit gauge invariance of this scheme /12/.Another important property of this approach is the following: all renormalization group functions of the Ovsiannikov equations appear to be independent of the ratios of external momenta / 7,12/, that allows us to put some of the external momenta equal to zero. It should be noted that it is only 't Hooft's scheme that enables us to make such a simplification without changing the results.

Then the Ovsiannikov equations obtained with the help of 't Hooft's technique are to be solved. Using the normalization conditions one can represent the solutions of these equations either as a perturbative series in the effective coupling constants /2/ or in the closed form /3,4/. However the most convenient form of renormalization group equations seems to be the Lie form, so it is attractive to proceed in the following way. Starting from the Ovsiannikov equations obtained up to a given order and using the normalization functions (calculated up to a previous order for the particular momentum dependence of the Green function under consideration) one finds the Lie equations in the same order of perturbation theory. As it has been noticed in Sec.3, the equations (9) and (15) are valid for an arbitrary renormalization scheme, because the function Ψ_Γ does not vary from one scheme to another. For instance, one can solve these equations in the frame of λ-scheme, which is attractive due to triviality of the normalization conditions. However to simplify the calculations one can choose to work with the equations in the form (9a), (15a) that implies to deal with 't Hooft's scheme. In a subsequent paper the described methods will be applied to the two-loop calculations.

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