

# THE SEVERAL GUISES OF THE BRST SYMMETRY

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## Abstract

We present several forms in which the BRST transformations of QCD in covariant gauges can be cast. They can be non-local and even not manifestly covariant. These transformations may be obtained in the path integral formalism by non standard integrations in the ghost sector or by performing changes of ghost variables which leave the action and the path integral measure invariant. For different changes of ghost variables in the BRST and anti-BRST transformations these two transformations no longer anticommute.

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## I. INTRODUCTION

BRST symmetry [1] is by now a familiar concept associated to the quantization of any gauge theory. It reflects in a deep way the gauge symmetry at the quantum level. For QCD in a covariant gauge there is a standard form for the BRST transformations

$$\begin{aligned}\delta A_\mu^a &= D_\mu c^a \\ \delta c^a &= -\frac{1}{2}g f^{abc} c^b c^c \\ \delta \bar{c}^a &= -\frac{i}{\xi} \partial_\mu A^{\mu a} \\ \delta \psi &= -g c^a \lambda^a \psi\end{aligned}\tag{1}$$

This form however is not unique. In fact several new symmetries of the quantum action of QED in Feynman gauge have been reported [2–4]. It has been pointed out however that they are just BRST transformations in non standard form [5]. In this paper we will elaborate on this point to extend it to the non-abelian case. We will show how the search for non standard BRST transformations, and by this we mean non local and/or not manifestly covariant BRST transformations, can be performed in a systematic way.

A reason for the existence of different forms of the BRST transformations is the fact that there is a set of changes of variables, not necessarily local, that leaves the ghost action invariant. There is also some freedom in the canonical formalism. For example, in the Batalin-Fradkin-Vilkovisky (BFV) formalism [6] we usually perform the path integration over the ghosts momenta to arrive at the transformations Eqs.(1). We could instead perform the integration over the ghosts themselves and leave the ghost momenta in the action. The resulting action is local after some changes of variables but the BRST transformations are in general non-local and not manifestly covariant.

In Section II we make a brief presentation of the BFV formalism applied to QCD to set up our conventions and set the stage for the next section. Then in Section III we derive the BRST transformations when we perform the alternative ghost path integration mentioned above. We show that there are two sets of BRST transformations, the usual one which is

covariant and local Eqs.(1) and another one which is not manifestly covariant and non local. In the next section we consider changes of ghost variables which leave the action and the path integral measure invariant. We particularize to the abelian case to avoid the unnecessary algebraic complications of the non-abelian structure. We show in particular that there exist changes of ghost variables which lead to BRST and anti-BRST transformations which do not anticommute. In the BFV formalism these changes of variables correspond to canonical transformations in the ghost sector. At last in Section V we make some final comments.

## II. RESUMÉ OF THE BFV FORMALISM FOR QCD

We will present in a very summarized way how the usual BRST transformations are obtained in BFV formalism [6].

The first step is to find out the constraint structure of QCD. After that we introduce the ghosts and their momenta to build up the BRST charge  $Q$ . The quantum QCD action is then [7]

$$S_q = \int d^4x \left( \Pi^{ia} \dot{A}_i^a + \Pi^{0a} \dot{A}_0^a + i\bar{\psi}\gamma^0\dot{\psi} + \dot{\mathcal{P}}^a \bar{c}^a + \dot{c}^a \bar{\mathcal{P}}^a - H_c - \{\Psi, Q\} \right) \quad (2)$$

where  $\Pi^{\mu a}$  are the momenta conjugated to  $A_\mu^a$ ;  $\mathcal{P}^a, \bar{\mathcal{P}}^a$  are the ghost momenta conjugated to the ghosts  $\bar{c}^a, c^a$ ;  $H_c$  is the canonical QCD Hamiltonian and  $\Psi$  is the gauge fixing fermion. The BRST charge is given by

$$Q = \int d^3x \left[ (D_i F^{i0a} + igJ_0^a) c^a + \frac{1}{2} f^{abc} \bar{\mathcal{P}}^a c^b c^c - i\mathcal{P}^a \Pi^{0a} \right] \quad (3)$$

The main assertion of the BFV formalism is that the path integral  $Z = \int D[\phi] \exp iS_q$  is independent of the gauge fixing fermion. Here  $D[\phi]$  is the usual Liouville measure over all fields and ghosts.

Proper choices of  $\Psi$  allows to recover the usual gauge conditions. Covariant gauges are implemented by the choice

$$\Psi = \int d^3x \left[ i\bar{c}^a \left( \frac{1}{2} \xi \Pi^{0a} + \partial_i A^{ia} \right) + \bar{\mathcal{P}}^a A_0^a \right] \quad (4)$$

For  $\xi = 1$  we get the Feynman gauge,  $\xi = 0$  the Landau gauge and  $\xi \rightarrow \infty$  the unitary gauge. By performing the functional integration over the momenta  $\Pi^{\mu a}$  we arrive at the effective action  $S$

$$\begin{aligned}
S &= S_{QCD} + S_{gf} + S_{gh} \\
S_{QCD} &= \int d^4x \left[ -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu a} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi \right] \\
S_{gf} &= - \int d^4x \frac{1}{2\xi} (\partial_\mu A^{\mu a})(\partial_\nu A^{\nu a}) \\
S_{gh} &= \int d^4x (i\bar{c}^a \partial_i D^i c^a + \dot{\mathcal{P}}^a \bar{c}^a - \bar{\mathcal{P}}^a D_0 c^a + i\bar{\mathcal{P}}^a \mathcal{P}^a)
\end{aligned} \tag{5}$$

where  $S_{QCD}$  is the classical QCD action,  $S_{gf}$  is the gauge fixing action and  $S_{gh}$  is the ghost action. The effective action  $S$  is then invariant under the BRST transformations generated by  $Q$  which have the form

$$\begin{aligned}
\delta A_i^a &= D_i c^a, & \delta A_0^a &= i\mathcal{P}^a \\
\delta c^a &= -\frac{1}{2} g f^{abc} c^b c^c, & \delta \bar{c}^a &= -\frac{i}{\xi} \partial_\mu A^{\mu a} \\
\delta \mathcal{P}^a &= 0, & \delta \bar{\mathcal{P}}^a &= D_i F^{0ia} - ig J_0^a - g f^{abc} \bar{\mathcal{P}}^b c^c \\
\delta \psi &= -g c^a \lambda^a \psi
\end{aligned} \tag{6}$$

where  $J_0^a = \bar{\psi} \lambda^a \gamma_0 \psi$  is the time component of the current.

At this stage we usually perform the path integration over  $\mathcal{P}^a$  and  $\bar{\mathcal{P}}^a$ . Integrating over  $\mathcal{P}^a$  gives a delta functional  $\delta(i\bar{\mathcal{P}}^a + \dot{c}^a)$  and integrating over  $\bar{\mathcal{P}}^a$  allow us to replace  $\bar{\mathcal{P}}^a$  by  $i\dot{c}^a$ . Then  $S_{gh}$  in Eqs.(5) gets its usual Faddeev-Popov form

$$S_{gh} = \int d^4x i\bar{c}^a \partial^\mu D_\mu c^a \tag{7}$$

and we get the usual BRST transformations Eqs.(1). Notice the importance of this last two integrals. We restore manifest covariance in the BRST transformations Eqs.(6) and we get a local and covariant ghost action Eq.(7). In the next section we will describe the results when we perform the integrations on other pair of ghost variables.

As usual the BRST transformations are nilpotent on-shell. The nilpotency fails only on  $\bar{c}^a$  and is proportional to the  $c^a$  field equation. Usually this can be overcome by the introduction

of an auxiliary field. In the BFV formalism, however, it corresponds to the situation where it is not performed the path integration over  $\Pi_0^a$ . If we call  $\lambda^a = \Pi_0^a + \frac{1}{\xi} \partial_\mu A^{\mu a}$  then the gauge fixed action has one more term and becomes

$$S_{gf} = \int d^4x \left[ -\frac{1}{2\xi} (\partial_\mu A^{\mu a})^2 + \frac{1}{2} \xi \lambda^a \lambda^a \right] \quad (8)$$

and the BRST transformations are the same as Eqs.(1) before except for  $\bar{c}^a$ . The new BRST transformations are then

$$\begin{aligned} \delta \bar{c}^a &= -\frac{i}{\xi} \partial_\mu A^{\mu a} + i\lambda^a \\ \delta \lambda^a &= \frac{1}{\xi} \partial^\mu D_\mu c^a \end{aligned} \quad (9)$$

In Section IV we will consider the case of QED with this extra field.

Besides the BRST transformations the quantum action is also invariant under anti-BRST transformations. In the BFV formalism the anti-BRST charge can be obtained from the BRST charge by interchanging ghosts by anti-ghosts in such a way that both charges anticommute. We then find that the anti-BRST transformations in a covariant gauge are

$$\begin{aligned} \bar{\delta} A_\mu^a &= D_\mu \bar{c}^a \\ \bar{\delta} c^a &= -\frac{i}{\xi} \partial_\mu A^{\mu a} \\ \bar{\delta} \bar{c}^a &= \frac{1}{2} g f^{abc} \bar{c}^b \bar{c}^c \\ \bar{\delta} \psi &= -g \bar{c}^a \lambda^a \psi \end{aligned} \quad (10)$$

It should be noticed that the anti-BRST symmetry is not a new symmetry. The anti-BRST charge has the same information content as the BRST charge and we could use anyone to generate physical states or to obtain Ward identities. Often both are used.

### III. NON-LOCAL BRST TRANSFORMATIONS

Consider the BFV formalism in the previous section up to the point where the integration over  $\Pi^{\mu a}$  was performed and Eqs.(5,6) were obtained. We will now perform the integration

over the ghost fields instead of their momenta. Integrating over  $\bar{c}^a$  gives  $\delta(i\partial_i D^i c^a - \dot{\mathcal{P}}^a) = \det(\partial_i D^i) \delta(ic^a - \frac{1}{\partial_i D^i} \dot{\mathcal{P}}^a)$ . Integrating now over  $c^a$  we can replace  $c^a = -i\frac{1}{\partial_i D^i} \dot{\mathcal{P}}^a$ . Then the ghost action in Eqs.(5) becomes

$$S_{gh} = \int d^4x (i\bar{\mathcal{P}}^a D_0 \frac{1}{\partial_i D^i} \dot{\mathcal{P}}^a + i\bar{\mathcal{P}}^a \mathcal{P}^a) \quad (11)$$

Notice the appearance of the non-local term in the ghost action as a result of this unusual integration. Notice also that the path integral measure has now an extra term  $\det(\partial_i D^i)$  which should be taken into account. We can overcome these two troubles by making judicious changes of variables. First perform the change of variables  $\dot{\mathcal{P}}^a \rightarrow ic^a, \bar{\mathcal{P}}^a \rightarrow i\bar{c}^a$  whose Jacobian is one. Then perform a second change of variables  $c^a \rightarrow -\partial_i D^i c^a$  whose Jacobian is  $\det^{-1}(\partial_i D^i)$ . As a result the contribution from the Jacobian to the path integral measure cancels out the contribution from the ghost integration. Also the non-local ghost action Eq.(11) becomes local and it takes the usual Faddeev-Popov form Eq.(7). The BRST transformations can now be obtained from Eqs.(6). They are

$$\begin{aligned} \delta A_i^a &= D_i c^a, & \delta A_0^a &= -\frac{1}{\partial_0} \partial_j D^j c^a \\ \delta c^a &= -\frac{1}{2} g f^{abc} c^b c^c \\ \delta \bar{c}^a &= -i \frac{1}{\partial_0} D_i F^{0ia} - g f^{abc} \frac{1}{\partial_0} (\bar{c}^b c^c) - g \frac{1}{\partial_0} J_0^a \\ \delta \psi &= -g c^a \lambda^a \psi \end{aligned} \quad (12)$$

We end up then with a local ghost action and a set of non-local and not manifestly covariant BRST transformations by performing the integration over the ghost fields instead of their momenta. The transformations Eqs.(12) leave the effective action invariant and are nilpotent as any good BRST transformation.

There are two other possibilities to perform the ghost integrations. If we perform the path integration over  $\bar{c}^a$  and  $\mathcal{P}^a$  we obtain the same result as before after proper changes of variables. If we integrate over  $\bar{\mathcal{P}}^a$  and  $c^a$  instead we get the usual BRST transformations Eqs.(1) also after proper change of variables.

Then in the BFV formalism we can arrive at a local ghost action, the Faddeev-Popov action, and two standard sets of BRST transformations which can be either covariant and local Eqs.(1) or not manifestly covariant and non-local Eqs.(12). It should also be noticed that both sets of BRST transformations reduce to each other on-shell. If we use the  $c^a$  and  $A_0^a$  field equations we can turn the non-local BRST transformations Eqs.(12) into the local ones Eqs.(1).

#### IV. CHANGES OF VARIABLES IN THE GHOST ACTION

From now on let us consider just the abelian case for the sake of simplicity. The ghost action is then  $S_{gh} = \int d^4x \ i\bar{c}\square c$ . This action allows a huge freedom to perform changes of variables which leave the path integration measure and the action itself invariant.

Let us consider first some cases with the non-local form of the BRST transformations. If we perform the following change of variables  $c \rightarrow i\frac{\partial_0}{\nabla^2}c$  and  $\bar{c} \rightarrow i\frac{\nabla^2}{\partial_0}\bar{c}$  whose Jacobian is one, then Eqs.(12) in the abelian case reduce to

$$\begin{aligned}\delta A_i &= i\frac{\partial_i}{\nabla^2}\dot{c}, & \delta A_0 &= ic \\ \delta c &= 0, & \delta\bar{c} &= \frac{1}{\nabla^2}\partial_i\dot{A}_i - A_0 + ig\frac{1}{\nabla^2}J_0 \\ \delta\psi &= -ig\left(\frac{1}{\nabla^2}\dot{c}\right)\psi\end{aligned}\tag{13}$$

These are precisely the transformations found in Ref. [2]. It has also been pointed out that they can be found by a canonical transformation in the ghost sector before any integration is performed [8].

Another change of variables  $c \rightarrow -\dot{c}$  and  $\bar{c} \rightarrow -\bar{c}$  (which also has Jacobian one) reduces the abelian form of Eqs.(12) to

$$\begin{aligned}\delta A_i &= -\partial_i\dot{c}, & \delta A_0 &= -\nabla^2c \\ \delta c &= 0, & \delta\bar{c} &= i\partial_i F^{0i} + gJ_0 \\ \delta\psi &= g\dot{c}\psi\end{aligned}\tag{14}$$

We then get the local but not manifestly covariant transformations found in Ref. [4].

Still another change of variables  $c \rightarrow \frac{\partial_0}{\nabla^2} c$  and  $\bar{c} \rightarrow \frac{\nabla^2}{\partial_0} \bar{c}$  this time in the abelian form of the usual BRST transformations Eqs.(1) produces

$$\begin{aligned}\delta A_\mu &= D_\mu \frac{1}{\nabla^2} \dot{c} \\ \delta c &= 0, \quad \delta \bar{c} = -\frac{i}{\xi} \frac{1}{\nabla^2} \partial_\mu \dot{A}^\mu \\ \delta \psi &= -g \left( \frac{1}{\nabla^2} \dot{c} \right) \psi\end{aligned}\tag{15}$$

These are the non-local transformations found in Ref. [3].

This procedure of performing changes of variables on the ghost fields can be easily generalized. Assume that  $F, G, \dots$  are operators which possess an adjoint  $F^t, G^t, \dots$  in the sense that

$$\int dx \phi F[\psi] = \int dx F^t[\phi] \psi\tag{16}$$

Notice that the effective action in the abelian case defines a bilinear metric  $\int dx \phi \psi$ . Assume also that these operators are field independent so that they commute with  $\partial_\mu$ . Let us consider also the extra field which makes the BRST transformations nilpotent off-shell as mentioned at the end of Section II. Consider now the change of variables

$$\begin{aligned}A_\mu &\rightarrow A_\mu, \quad \lambda \rightarrow \lambda, \quad \psi \rightarrow \psi \\ c &\rightarrow F[c], \quad \bar{c} \rightarrow (F^{-1})^t[\bar{c}]\end{aligned}\tag{17}$$

whose Jacobian is one. Let us call this change of variables a  $F$  transformation. Then the abelian ghost action remains invariant under this  $F$  transformation and the local abelian BRST transformations Eqs.(1, 9) become

$$\begin{aligned}\delta A_\mu &= \partial_\mu F[c], \quad \delta \lambda = \frac{1}{\xi} \square F[c] \\ \delta c &= 0, \quad \delta \bar{c} = F^t \left[ -\frac{i}{\xi} \partial^\mu A_\mu + i\lambda \right] \\ \delta \psi &= g\psi F[c]\end{aligned}\tag{18}$$



and clearly generalizes Eqs.(15). If instead we perform the change of variables in the abelian non-local BRST transformations Eqs.(12) we get the generalization of the BRST transformations Eqs.(13, 14).

We can now consider the following situation. Consider a  $F$  transformation and the resulting BRST transformations Eqs.(18). Consider a  $G$  transformation defined as

$$\begin{aligned} A_\mu &\rightarrow A_\mu, & \lambda &\rightarrow \lambda, & \psi &\rightarrow \psi \\ c &\rightarrow (G^{-1})^t[c], & \bar{c} &\rightarrow G[\bar{c}] \end{aligned} \quad (19)$$

and the resulting **anti**-BRST transformations, that is,

$$\begin{aligned} \bar{\delta}A_\mu &= \partial_\mu G[c], & \bar{\delta}\lambda &= \frac{1}{\xi} \square G[\bar{c}] \\ \bar{\delta}c &= G[-\frac{i}{\xi} \partial^\mu A_\mu + i\lambda] & \bar{\delta}\bar{c} &= 0 \\ \bar{\delta}\psi &= g\psi G[\bar{c}] \end{aligned} \quad (20)$$

This  $G$  transformation also leaves the effective action invariant. We then end up with a set of  $F$  transformed BRST transformations Eqs.(18) and a set of  $G$  transformed anti-BRST transformations Eqs.(20) and the abelian effective action. It is clear that the  $F$  transformed BRST and the  $G$  transformed anti-BRST transformations are nilpotent. However the anticommutator of a  $F$  transformed BRST transformation Eqs.(18) with the  $G$  transformed **anti**-BRST transformations Eqs.(20) does not vanish. If we denote this anticommutator by  $\Delta$  we obtain

$$\begin{aligned} \Delta A_\mu &= i\partial_\mu(GF^t - FG^t)[\lambda - \frac{1}{\xi} \partial^\nu A_\nu] \\ \Delta c &= \Delta \bar{c} = 0 \\ \Delta \lambda &= i\frac{1}{\xi} \square(GF^t - FG^t)[\lambda - \frac{1}{\xi} \partial^\mu A_\mu] \\ \Delta \psi &= -ig\psi(GF^t - FG^t)[\lambda - \frac{1}{\xi} \partial^\mu A_\mu] \end{aligned} \quad (21)$$

Notice that these transformations have ghost number zero. They do not act on the ghosts and behave as gauge transformations on  $A_\mu$  and  $\psi$ . We easily verify that Eqs.(21) are a

symmetry of the effective action as well. We also find that they correspond to a new change of variables defined by

$$\begin{aligned}
A_\mu &\rightarrow A_\mu + i\partial_\mu(H - H^t)\left[\lambda - \frac{1}{\xi}\partial^\nu A_\nu\right] \\
c &\rightarrow c, \quad \bar{c} \rightarrow \bar{c} \\
\lambda &\rightarrow \lambda + \frac{i}{\xi}\square(H - H^t)\left[\lambda - \frac{1}{\xi}\partial^\nu A_\nu\right] \\
\psi &\rightarrow \psi - ig\psi(H - H^t)\left[\lambda - \frac{1}{\xi}\partial^\nu A_\nu\right]
\end{aligned} \tag{22}$$

Let us call this change of variables an  $H$  transformation. They correspond to the transformations Eqs.(21) with  $H = GF^t - FG^t$ . This change of variables has Jacobian equals to one and also leave the effective action invariant.

Then the freedom to perform changes of variables which leave the ghost action and the path integral measure invariant reflects itself in the BRST symmetry by allowing another set of transformations of the type Eqs.(22). As a consequence the anticommutator of the BRST and anti-BRST transformations does not need to vanish and is proportional to an  $H$  transformation Eqs.(22).

This can also be seen when we build the BRST charge in the BFV formalism. In the abelian case the BRST charge and the anti-BRST charge are

$$\begin{aligned}
Q &= \int d^3x (\partial^i A_i c - i\Pi_0 \mathcal{P}) \\
\bar{Q} &= \int d^3x (\partial^i A_i \bar{c} + i\Pi_0 \bar{\mathcal{P}})
\end{aligned} \tag{23}$$

respectively. It is easily verified that they anticommute. Now we can build the  $F$  transformed BRST charge where the  $F$  transformation on the ghost momenta is defined as  $\mathcal{P} \rightarrow F[\mathcal{P}]$  and  $\bar{\mathcal{P}} \rightarrow (F^{-1})^t[\bar{\mathcal{P}}]$ . We easily verify that the  $F$  transformation is a canonical transformation. Now because the  $F$  and  $G$  transformations leave the effective action invariant we could build the BRST charge with the  $F$  transformed ghosts and the anti-BRST charge with the  $G$  transformed ghosts (the  $G$  transformation on  $\mathcal{P}$  and  $\bar{\mathcal{P}}$  being defined in a similar way to the  $F$  transformation). Then the anticommutator of the BRST and anti-BRST charges no

longer vanishes and is proportional to  $FG^t - F^tG$ . We then see that in the BFV formalism the changes in the ghosts variables we have been working with correspond to canonical transformations on the ghosts. The non vanishing of the anticommutator of the BRST and anti-BRST transformations is due to the fact that the charges are build with ghosts which have been subject to different canonical transformations.

Since the effective action is invariant under BRST and anti-BRST transformations it is also invariant under any linear combination of them. If we take the original transformations the combined transformation is nilpotent since each of the original transformations is by itself nilpotent as is their anticommutator. We could however consider the sum of the  $F$  transformed BRST with the  $G$  transformed anti-BRST transformations. We then have a set of transformations which do not have a well defined ghost number, leave the effective action invariant and are not nilpotent because of Eqs.(21). This is the origin of the non-nilpotent symmetry found in Ref. [3].

## V. CONCLUSIONS

We have shown that the effective action of QCD in a covariant gauge is invariant under non-local and even not manifestly covariant BRST transformations either as a result of the BFV path integral formulation or as a change of ghost variables which leave the effective action and the path integral measure invariant. They just reflect the basic BRST symmetry in different forms. They are symmetries of the full interacting quantum theory (in the absence of anomalies) but do not entail any new Ward identity besides those obtained from the usual BRST transformations. It also shows the power of the Hamiltonian formalism. Although the non standard form of the BRST transformations can be found in the Lagrangian formalism its origin remains obscure and its dependence on other known symmetries can not be traced. In the BFV formalism all these issues can be clearly analysed.

It is worth remarking that it is possible for a gauge fixed action to have further symmetries besides the BRST symmetry. One well known example is the non-abelian Chern-Simons

theory in Landau gauge in  $2 + 1$  dimensions. It has a rigid vector supersymmetry [9] which is independent of the BRST symmetry. In fact this vector supersymmetry and the BRST symmetry are part of a more general algebra which is a contraction of the exceptional Lie superalgebra  $D(2|1; \alpha)$  [10]. That this vector supersymmetry is a truly new symmetry manifests itself in the existence of a new Ward identity which relates the gauge and ghost inverse propagators [9].

Our discussion on changes of ghost variables in Section IV were done only for the abelian case and in the situation where the ghost transformations do not involve any field. In trying to consider a field dependent  $F$  transformation we were led to very complicated expressions. Also the non-abelian case became rather involved. We still miss a suitable formalism to handle such situations.

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