Regularization of Supersymmetric Theories: Recent Improvements

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Recent progress concerning regularization of supersymmetric theories is reviewed. Dimensional reduction is reformulated in a mathematically consistent way, and an elegant and general method is presented that allows to study the supersymmetry-invariance of dimensional reduction in an easy manner. This method is applied to several supersymmetry identities at the one- and two-loop level, and thus the extent to which dimensional reduction is known to preserve supersymmetry is significantly enlarged.

1. INTRODUCTION

Regularization by dimensional reduction (DRED) [1] is the most common regularization for supersymmetric theories. In contrast to ordinary dimensional regularization [2, 3], DRED has been shown to preserve supersymmetry in several cases [4–6]. Nevertheless, DRED has always been known to be mathematically inconsistent [7], and as a consequence there is no general proof that it preserves supersymmetry in all cases.

The fact that no consistent supersymmetric and gauge-invariant regularization is known leads immediately to fundamental questions: Are supersymmetric theories renormalizable at all? Are there genuine supersymmetry anomalies? These questions have been studied extensively in a regularization-independent way, and the answers are Yes and No, respectively [8–10].

But the problems of DRED also lead to very practical questions: (1) Does the mathematical inconsistency matter in practical calculations? (2) To what extent is DRED supersymmetric? These questions are particularly important in view of the SPA ("Supersymmetry Parameter Analysis") project [11], where loop calculations within supersymmetry are required and supersymmetry parameters are defined in the $\overline{DR}$ scheme. The $\overline{DR}$ scheme is equivalent to using DRED as a regularization and to perform minimal subtraction of the divergent terms.

If DRED would break supersymmetry in a certain calculation, additional (often finite) counterterms would have to be found and added in order to restore supersymmetry. Hence, in such a case the $\overline{DR}$ scheme as such could not be used and would have to be modified. Moreover, the technical determination of such supersymmetry-restoring counterterms is often tedious [6].

In the present paper we review the results of [12], where DRED was studied with three aims:

(1) DRED should be redefined without a mathematical inconsistency.

(2) A general method should be found to study the supersymmetry-invariance of DRED.

(3) The general method should actually be applied to verify that DRED preserves supersymmetry in several non-trivial cases of practical interest.

It turns out that the consistent formulation of DRED allows to prove the quantum action principle, which is a theorem that can be used as the key ingredient in the study of symmetry-properties of DRED. We will describe the consistent formulation of DRED in Sec. 2, the quantum action principle and its role in Sec. 3; the desired method and its applications are discussed in Sec. 4.

In the remainder of this introduction we mention another problem of DRED that is important for the SPA project and the question to what extent the $\overline{DR}$ scheme can be used for hadronic processes. In [13, 14] an apparent mismatch between the DRED-result for the process $gg \to t\bar{t}$ and the expectation from QCD-factorization has been reported. In the case of massless quarks instead of $t\bar{t}$, the transition from DRED to ordinary dimensional regularization for the NLO-corrections involves a simple convolution with the LO cross section. In the case of massive $t\bar{t}$ in the final state, however, the transition involves additional terms that do not have the expected factorized structure. It is an important task to understand this puzzling result and to reconcile DRED with QCD-factorization [15].

2. MATHEMATICAL CONSISTENCY

In DRED, only momenta and momentum integrals are continued from 4 to D dimensions, while γ-matrices and gauge fields remain 4-dimensional objects. Accordingly, two types of metric tensors can appear in the computation of Feynman diagrams: the 4-dimensional $g^{\mu\nu}$ can appear e.g. in the numerator of vector boson propagators, and the D-dimensional $\hat{g}^{\mu\nu}$ can appear in the result of a D-dimensional integral $\int d^D p[p^\mu p^\nu f(p^2)]$. Defining also a $(4-D)$-dimensional metric tensor $\tilde{g}^{\mu\nu}$, they satisfy the following relations:

$$g^{\mu\nu} = \hat{g}^{\mu\nu} + \tilde{g}^{\mu\nu} \qquad g^{\mu\nu} g_{\mu\nu} = 4 \qquad \hat{g}^{\mu\nu}\hat{g}_{\mu\nu} = D \qquad \tilde{g}^{\mu\nu}\tilde{g}_{\mu\nu} = 4 - D \tag{1a}$$

$$g^{\mu\nu}\hat{g}_\nu{}^\rho = \hat{g}^{\mu\rho} \qquad g^{\mu\nu}\tilde{g}_\nu{}^\rho = \tilde{g}^{\mu\rho} \qquad \hat{g}^{\mu\nu}\tilde{g}_\nu{}^\rho = 0 \tag{1b}$$

These relations correspond to a decomposition of the 4-dimensional space into a D-dimensional subspace and an orthogonal $(4-D)$-dimensional subspace. Using $\hat{g}^{\mu\nu}$ and $\tilde{g}^{\mu\nu}$ as projectors onto these subspaces we can define $\hat{a}^\mu = \hat{g}^{\mu\nu} a_\nu$, $\tilde{a}^\mu = \tilde{g}^{\mu\nu} a_\nu$ for any 4-dimensional object a^μ. In particular this is possible for the 4-dimensional ϵ-tensor, and we can write down the product

$$\hat{\epsilon}^{\mu\nu\rho\sigma}\,\tilde{\epsilon}_{\alpha\beta\gamma\delta}\,\hat{\epsilon}_{\mu\nu\rho\sigma}\,\tilde{\epsilon}^{\alpha\beta\gamma\delta}\,. \tag{2}$$

If we now use the 4-dimensional relation

$$\epsilon^{\mu_1\mu_2\mu_3\mu_4}\,\epsilon^{\nu_1\nu_2\nu_3\nu_4} \propto \det((g^{\mu_i\nu_j})) \tag{3}$$

we can evaluate the product (2) in two ways. If (3) is applied to the first and second factor in (2), we obtain zero, but applying (3) to factors 1–3 yields $D(D-1)(D-2)(D-3)$ and applying it to factors 2–4 yields $\epsilon(\epsilon-1)(\epsilon-2)(\epsilon-3)$, where $\epsilon = 4 - D$. Therefore, evaluating (2) in these two ways leads to the two results

$$0 = D(D-1)^2(D-2)^2(D-3)^2(D-4). \tag{4}$$

This is mathematically inconsistent with D taking arbitrary values. This fundamental inconsistency of DRED was already discovered in Ref. [7], and it can be rewritten in several ways involving ϵ-tensors, γ_5, or only metric tensors (see e.g. [16]).

It is important to note that the inconsistency (4) is not derived from the relations (1) alone but that the purely 4-dimensional relation (3) is necessary as well. In [12] it is shown that the rules (1) are in fact completely consistent. Well-defined objects $g^{\mu\nu}$, $\hat{g}^{\mu\nu}$, $\tilde{g}^{\mu\nu}$ are explicitly constructed such that the relations (1) are satisfied. This ensures that any application of (1) alone will never lead to an inconsistent result such as (4). The explicit objects constructed in Ref. [12], however, *do not satisfy* eq. (3), which is why the inconsistency is avoided.[1]

Similarly to $g^{\mu\nu}$, $\hat{g}^{\mu\nu}$, $\tilde{g}^{\mu\nu}$, γ-matrices can be constructed that satisfy

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}, \qquad \gamma^\mu\gamma_\mu = 4, \tag{5}$$

but that do not satisfy further 4-dimensional relations like Fierz relations. For the evaluation of many Feynman diagrams, eqs. (1), (5) are sufficient. Therefore, for a wide range of applications, the consistent version of DRED, where only (1) and (5) may be used, does not differ from the traditional version, where (3) or Fierz identities might be used in addition.

The consistent formulation of DRED has a crucial consequence. Beyond the practical evaluation of Feynman diagrams, it allows to give a general proof of the quantum action principle. This will be exploited in the next section.

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[1] In particular, the 4-dimensional metric tensor $g^{\mu\nu}$ appearing here *does not have* the index representation $g^{00} = -g^{ii} = 1$ for $i = 1, 2, 3$ and $g^{\mu\nu} = 0$ otherwise. $g^{\mu\nu}$, $\hat{g}^{\mu\nu}$, $\tilde{g}^{\mu\nu}$ have to be more complicated objects.

3. SUPERSYMMETRY OF DRED AND THE QUANTUM ACTION PRINCIPLE

It is an important open question whether or to what extent DRED preserves supersymmetry. So far, several supersymmetry identities between propagators and/or three-point functions have been shown to be valid in DRED at the one-loop level [4–6]. However, these checks do not even exhaust all cases of practical interest; e.g. supersymmetry Slavnov-Taylor identities relating four-point functions and/or two-loop identities have not been checked. The traditionally used methods are tedious and by using them it is hard to extend the checks performed in the literature.

Our second aim is therefore to develop a method that simplifies the study of supersymmetry in DRED. Generally, supersymmetry Ward or Slavnov-Taylor identities can be written in the form

$$\delta_{\rm SUSY}\langle T\phi_1\dots\phi_n\rangle^{\rm DRED} \stackrel{(?)}{=} 0, \tag{6}$$

where the (?) indicates that the identity is not necessarily valid in DRED but it is our task to verify it. In Refs. [4–6] this verification was done by explicitly evaluating all Green functions on the left-hand side of (6) and checking that they all add up to zero. A drastically simpler way to check (6) can be based on the quantum action principle, which relates the left-hand side of (6) to a simpler Green function (see Ref. [12] for more details, a heuristic explanation using the path integral and the proof in DRED):

$$i\,\delta_{\rm SUSY}\langle T\phi_1\dots\phi_n\rangle^{\rm DRED} =\langle T\phi_1\dots\phi_n\Delta\rangle^{\rm DRED}\ , \qquad\qquad \text{where } \Delta=\int d^Dx\delta_{\rm SUSY}\mathcal{L}. \tag{7}$$

The right-hand side of the quantum action principle is a single Green function involving the insertion of the composite operator Δ, which can be obtained from the supersymmetry variation of the regularized Lagrangian. The caveat here is that the quantum action principle itself is a regularization-dependent statement and it is not obviously valid in DRED. However, using the consistent formulation presented in the previous section, (7) can be shown to hold in DRED [12]. The proof turns out to be analogous to the corresponding proof for dimensional regularization [3].

Hence a given supersymmetry Slavnov-Taylor identity can be checked by simply verifying that $\langle T\phi_1\dots\phi_n\Delta\rangle^{\rm DRED}$ vanishes. In the next section, we will show how easily this can be done in several non-trivial examples.

Before applying the quantum action principle explicitly to supersymmetry Slavnov-Taylor identities, it is convenient to introduce the notation used in Refs. [6, 8, 9] and in particular for the Slavnov-Taylor identity of the MSSM [10]. All Slavnov-Taylor identities of the form (6) can be combined into a single identity $S(\Gamma^{\rm DRED})=0$, where $\Gamma^{\rm DRED}$ is the vertex functional of one-particle irreducible (1PI) Green functions, regularized using DRED, and $S(\cdot)$ is a bilinear operator. Particular 1PI Green functions are obtained as $\Gamma_{\phi_1\dots}=(\delta\Gamma/\delta\phi_1\dots)|_{\phi_i=0}$, and identities for particular Green functions analogous to (6) can be rederived by taking derivatives like

$$\left.\frac{\delta^{n+1}S(\Gamma^{\rm DRED})}{\delta\phi_n\dots\delta\phi_1\delta\epsilon}\right|_{\phi_i=0} \stackrel{(?)}{=} 0, \tag{8}$$

where ϵ denotes the supersymmetry transformation parameter.

The quantum action principle then takes the form

$$S(\Gamma^{\rm DRED})=i[S(\Gamma_{\rm cl})]\cdot\Gamma^{\rm DRED}, \tag{9}$$

where $[\Delta]\cdot\Gamma^{\rm DRED}$ denotes the insertion of an operator Δ into the 1PI vertex functions analogous to the insertion on the right-hand side of eq. (7). $\Gamma_{\rm cl}$ denotes the regularized classical action $\int d^Dx\mathcal{L}$.

4. SUPERSYMMETRY OF DRED UP TO THE TWO-LOOP LEVEL

We are now going to apply the strategy of the previous section to study several supersymmetry identities in DRED. That is, we consider identities of the form (8) and replace the left-hand side by

$$\left(i[S(\Gamma_{\rm cl})]\cdot\Gamma^{\rm DRED}\right)_{\phi_n\dots\phi_1\epsilon}, \tag{10}$$

the 1PI Green function with insertion of the operator $S(\Gamma_{\rm cl})$ and external fields $\epsilon\phi_1\dots\phi_n$. The corresponding identity (8) is valid in DRED precisely if (10) vanishes; in general, (10) constitutes a possible violation of eq. (8).

4.1. Insertion operator and its Feynman rule

As a first step, the insertion operator $[S(\Gamma_{\rm cl})]$ has to be evaluated; it is a major advantage that this operator is universal and the evaluation has to be performed only once. The result for a general supersymmetric gauge theory has been given in [12]. We quote here only the part related to matter field interactions:

$$S(\Gamma_{\rm cl}) = -g\int d^Dx\left[2(\overline{\psi}P_R\epsilon)(\overline{\tilde{g}}P_L\psi) + 2(\bar{\epsilon}P_L\psi_j)(\overline{\psi}_iP_R\tilde{g}_{ij}) + (\overline{\psi}_i\gamma^\mu P_L\psi_j)(\bar{\epsilon}\gamma_\mu\tilde{g}_{ij}) + \ldots\right]. \quad (11)$$

Here ϕ and ψ denote the scalar and fermionic components of chiral multiplets; $\tilde{g}$ denotes the gaugino field. All terms in $S(\Gamma_{\rm cl})$ are four-fermion operators. In strictly 4 dimensions, where Fierz identities can be used, $S(\Gamma_{\rm cl}) = 0$, but in DRED, where Fierz identities are invalid, the insertion of $S(\Gamma_{\rm cl})$ into Green functions could lead to non-vanishing breakings (10).

As a second step, the Feynman rule corresponding to the insertion of $S(\Gamma_{\rm cl})$ into a diagram has to be determined. For our applications, diagrams of the basic topology shown in Fig. 1(a) are most relevant. In these diagrams, the $\tilde{g}$ and $\overline{\psi}$ leaving the vertex corresponding to $S(\Gamma_{\rm cl})$ are connected to a closed fermion loop via emission of a scalar field $\phi^\dagger$. Additional boson lines can be attached in the actual applications. Denoting the string of γ-matrices attached to the external ψ line as A and the γ-string associated to the closed fermion loop as B, the Feynman rule for this diagram reads

$$(\gamma^\mu B\gamma_\mu - 2P_RB^C)P_LA - 2P_LA\,\mathrm{Tr}(P_RB). \quad (12)$$

Here $P_{R,L} = \frac{1}{2}(1\pm\gamma_5)$ and B^C is derived from B using the rule $(\gamma^{\mu_1}\ldots\gamma^{\mu_n})^C = (-1)^n\gamma^{\mu_n}\ldots\gamma^{\mu_1}$. Again this expression (12) vanishes identically in strictly four dimensions.

In DRED, however, where only the rules (1), (5) can be applied, eq. (12) does not vanish in general, but it does vanish if B does not contain more than three γ-matrices. This observation turns out to be sufficient for all applications described below.

4.2. Examples

The first example we consider is the identity $\frac{\delta^3 S(\Gamma)}{\delta\phi^\dagger\delta\psi\delta\bar{\epsilon}} = 0$. Its explicit form reads

$$0 = \Gamma_{\psi\bar{\epsilon}Y_{\phi_i}}\Gamma_{\phi^\dagger\phi_i} - \Gamma_{\phi^\dagger Y_{\psi_i}\bar{\epsilon}}\Gamma_{\psi\overline{\psi}_i}, \quad (13)$$

and it expresses the fundamental supersymmetry relation between the ϕ and ψ self energies, including the equality of the ϕ and ψ masses. Eq. (13) has already been studied extensively, and it has been shown to be valid in DRED at the one-loop level in various supersymmetric models [6]. The checks performed in Refs. [6] involve the evaluation of all four Green functions in eq. (13). In particular the necessity to evaluate also the Green functions involving Y_{ϕ_i} and Y_{ψ_i}, corresponding to loop-corrected supersymmetry transformations of ϕ_i and ψ_i, makes the checks rather tedious.

Examining identity (13) becomes almost trivial if the quantum action principle is used. The possible violation of (13) is given by

$$\left(i[S(\Gamma_{\rm cl})]\cdot\Gamma^{\rm DRED}\right)_{\phi^\dagger\psi\bar{\epsilon}}, \quad (14)$$

and the diagram in Fig. 1(a) is the single one-loop contributing to this violation. In this diagram, the γ-string B, corresponding to the closed loop, contains at most two γ-matrices. Hence, the expression (12) and the whole diagram vanish, and thus there is no violation of (13) in DRED at the one-loop level.

It is possible to extend this analysis to the two-loop level. There are several two-loop diagrams corresponding to the possible violation (14); the one with the most γ-matrices in the fermion loop is shown in Fig. 1(b). After integrating over the fermion loop momentum, this diagram contains only up to three γ-matrices in the γ-string B, and therefore it vanishes. It can be easily seen that the same is true for all two-loop diagrams contributing to (14). This shows that the propagator identity (13) is valid in DRED even at the two-loop level.

In a similar way one can derive and study an identity relating the loop-corrected supersymmetry transformations $\Gamma_{\psi\bar{\epsilon}Y_{\phi_i}}$ and $\Gamma_{\phi^\dagger Y_{\psi_i}\bar{\epsilon}}$. Such identities are generally important because they express the fact that in spite of loop corrections to the supersymmetry transformations, the supersymmetry algebra still holds. In turn, this is a necessary condition for identities like (13) to correspond to supersymmetry relations. In Refs. [6] several supersymmetry algebra identities have been discussed and verified at the one-loop level.

We can use again the quantum action principle to write the possible violation of the identity relating $\Gamma_{\psi\bar{\epsilon}Y_{\phi_i}}$ and $\Gamma_{\phi^\dagger Y_{\psi_i}\bar{\epsilon}}$ in the form (10). It turns out that there is no corresponding one-loop diagram at all. Moreover, it can be easily shown that all two-loop diagrams contributing to the violation of the identity vanish [12].

Therefore, in this approach not only the results found in [6] become completely obvious, but it is also very easy to extend the results to the two-loop level.

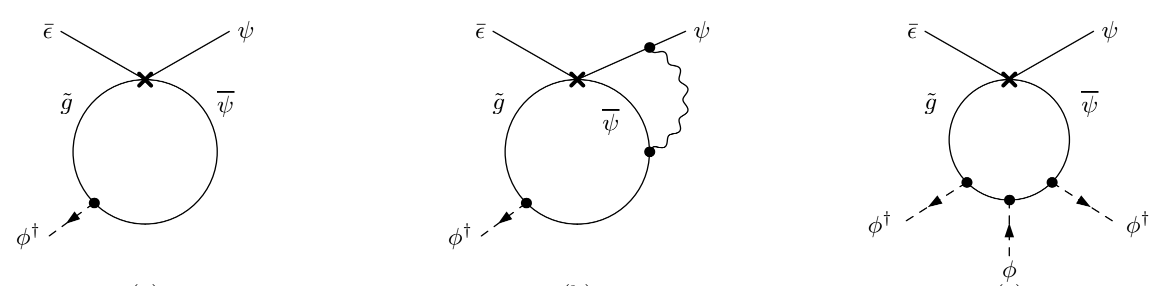

Figure 1: (a): Basic topology of a diagram involving an insertion of $S(\Gamma_{\rm cl})$, eq. (12). Additional boson lines have to be attached in the actual diagrams. In the text, the γ-string attached to the second external ψ line is denoted as A, the γ-string attached to the closed fermion loop as B.
(b): A two-loop diagram corresponding to $([S(\Gamma_{\rm cl})]\cdot\Gamma^{\rm DRED})_{\phi^\dagger\psi\bar{\epsilon}}$, eq. (14). Such two-loop diagrams involving a virtual vector boson are the only ones where the γ-string B can contain three γ-matrices after integration over the fermion loop momentum.
(c):One-loop diagram corresponding to $([S(\Gamma_{\rm cl})]\cdot\Gamma^{\rm DRED})_{\phi^\dagger\phi^\dagger\phi\psi\bar{\epsilon}}$, eq. (15).

The final example we consider concerns the ϕ^4 interaction. It is well-known that in supersymmetric models the ϕ^4 terms in the scalar potential are completely determined in terms of gauge and Yukawa couplings and do not involve free parameters. This is in particular the origin of the Higgs boson mass predictions in the MSSM, which has been computed up to the two-loop level (see [17] for a review). However, the corresponding Slavnov-Taylor identity describing the correct treatment of the ϕ^4 interaction at the loop level has never been verified, not even at the one-loop level.

This Slavnov-Taylor identity for the ϕ^4 interaction is given by $\frac{\delta^5 S(\Gamma)}{\delta\phi^\dagger\delta\phi\delta\phi^\dagger\delta\psi\delta\bar{\epsilon}}=0$, and according to (10) its possible violation is given by

$$\left(i[S(\Gamma_{\rm cl})]\cdot\Gamma^{\rm DRED}\right)_{\phi^\dagger\phi\phi^\dagger\psi\bar{\epsilon}}. \tag{15}$$

The diagram in Fig. 1(c) is the only one-loop diagram contributing to this Green function (up to permutations). As in the previous cases, after integrating over the fermion loop momentum, the γ-string B can contain at most three γ-matrices, here corresponding to $\not{p}_i$ for the three independent incoming momenta p_i. Hence the violation (15) vanishes and the ϕ^4 Slavnov-Taylor identity is valid in DRED at the one-loop level.

5. CONCLUSIONS

We have studied DRED with three aims presented in the introduction. First DRED could be redefined in a mathematically consistent way. The difference to the traditional formulation concerns only the validity of Fierz and similar relations but is not relevant in a wide range of applications.

In a second step a general method to study supersymmetry identities in DRED was developed based on the quantum action principle (7), (9). Using the consistent formulation of DRED, the quantum action principle could be established in DRED. Supersymmetry Slavnov-Taylor identities of the form (8) are then generally violated by the expression $\left(i[S(\Gamma_{\rm cl})] \cdot \Gamma^{\rm DRED}\right)_{\phi_n \ldots \phi_1 \epsilon}$, eq. (10). This is a Green function involving the insertion of the operator $S(\Gamma_{\rm cl})$, which has been evaluated explicitly, see eq. (11).

Finally, this method has been applied to study several supersymmetry identities of practical interest. The identities for propagators, eq. (13), and for the corresponding supersymmetry transformations have been considered already in Refs. [6], but only at the one-loop level. We have shown here that rederiving the one-loop results using the described method is very easy, and we could present the verification of these identities at the two-loop level. In addition, the identity for the ϕ^4 interaction has been verified at the one-loop level.

In conclusion, the status of DRED has been improved by establishing mathematical consistency, the quantum action principle and the validity of supersymmetry identities up to the two-loop level. A crucial outcome is that using the developed method, studying supersymmetry identities is dramatically simplified beyond the considered examples. For the future it will be important to further study the properties of DRED, in particular to verify that DRED preserves supersymmetry at least to the level required for loop calculations of LHC- or ILC-observables. This goal will require more work, but it has come within reach with the results presented here.

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