On Nonlinear Superconformal Algebras With $N > 4$*

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ABSTRACT

We discuss the structure, realizations and quantum BRST operators of a class of nonlinear superconformal algebras with $N > 4$.

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1. Introduction

A class of superconformal algebras with $N$-extended supersymmetry were classified long ago [1]. They contain a single spin 2 generator and multiplets of other generators of spin decreasing by half units down to minimum spin $2 - \frac{1}{2}N$. These are linear algebras and the $N = 1, 2, 4$ cases have found important and interesting applications in string theory, but beyond $N = 4$, concordant with the fact that negative dimension generators set in, no such applications have emerged so far.

One way to extend the supersymmetry beyond $N = 4$ is to allow nonlinearities in the algebra. The mildest such nonlinearity would be quadratic. Requiring one spin 2 generator, multiplets of spin 3/2 and spin 1 generators, generalizations involving quadratic nonlinearity have been found [2,3]. They contain the energy momentum tensor, spin 3/2 currents in the fundamental representation of $so_N$ or $u_N$, and spin 1 currents in the adjoint representation of the same algebras. A characteristic feature of these algebras is that the OPE of two spin 3/2 currents contains an operator bilinear in spin 1 currents.

In general, a convenient way of characterizing the quadratically nonlinear algebras of the above type is to specify a pair $(g, \rho)$ where $g$ is the (super) Lie algebra and $\rho$ is the representation carried by the spin 3/2 currents. All possibilities for this pair (as determined by the closure of the algebra) have been classified in [4-8], including the cases when the spin 3/2 generators are commuting (corresponding to the quasi-superconformal algebras) and the doubly graded superalgebras where the affine Lie algebra sector itself is based on a superalgebra. The (quasi) superconformal algebras with simple $g$ and irreducible $\rho$ are listed below.

| $g$ | $\rho$ | $h^{'\gamma}_g$ | $i_{\rho}$ | $\psi^2$ |
|-----|--------|----------------|------------|---------|
| $D_n$ | $2n$ | $2n - 2$ | $1$ | $2$ |
| $B_n$ | $2n + 1$ | $2n - 1$ | $1$ | $4$ |
| $B_3$ | $8_s$ | $5$ | $1$ | $4$ |
| $G_2$ | $7$ | $4$ | $1$ | $6$ |
| $C_n$ | $2n$ | $n + 1$ | $1/2$ | $4$ |
| $A_5$ | $20$ | $6$ | $3$ | $2$ |
| $D_6$ | $32$ | $10$ | $4$ | $2$ |
| $E_7$ | $56$ | $18$ | $6$ | $2$ |
| $C_3$ | $14$ | $4$ | $5/2$ | $4$ |
| $A_1$ | $4$ | $2$ | $5/2$ | $2$ |

Our main motivation for studying these algebras is the possibility of their use in constructing a novel string theory with $N > 4$ worldsheet local supersymmetry. Our recent work [9] on quadratically nonlinear superconformal algebras dealt with the construction of
the quantum BRST operator, which is a step towards this goal. It generalizes the work of ref. [10] where an elegant formula was derived for the classical and quantum BRST operator for a large class of quadratically nonlinear algebras. In section 2, we shall summarize the results of refs. [9,10]. The issue of free field realization is another important aspect of string theory construction. In section 3 we summarize result of ref. [11] which furnishes the most general realization known so far. Quadratic nonlinearity is the mildest one that can be introduced. Another kind of highly nonlinear algebra of the type listed in the Table are generated by the energy-momentum tensor $T(z)$, the dimension 3/2 supercurrents $G^i(z), i = 1, \ldots, \dim \rho := d$ and the dimension 1 currents $J^a(z), a = 1, \ldots, \dim g := D$. The products $T(z)T(\omega)$, $T(z)G^i(\omega)$ and $T(z)J^a(\omega)$ are standard. The remanining part of the operator product algebra takes the form

$$G^i(z)G^j(\omega) = \frac{b\eta^{ij}}{(z-\omega)^3} + \frac{\sigma \lambda^i_a J^a(\omega)}{(z-\omega)^2} + \frac{1}{2} \frac{\sigma \lambda^i_a \partial J^a(\omega)}{(z-\omega)} + \frac{2\eta^{ij}T(\omega)}{(z-\omega)} + \gamma P^{ij}(J^a J^b)(\omega) + \cdots,$$

(2.1a)

$$J^a(z)G^i(\omega) = \frac{-\lambda^i_a G^i(\omega)}{(z-\omega)} + \cdots,$$

(2.1b)

$$J^a(z)J^b(\omega) = \frac{-\frac{1}{2} \eta^{ab} \delta^2}{(z-\omega)^2} + \frac{f^{abc}J^c(\omega)}{(z-\omega)} + \cdots,$$

(2.1c)

where the generators $\lambda^a_{ij}$ and the structure constants $f^{abc}$ satisfy the relations [4]

$$\lambda^a_{aij} \lambda^k_{bij} - \lambda^a_{bjk} \lambda^k_{aij} = f^{abc} \lambda^c_{ij}, \quad \lambda^a_{aij} \lambda^b_{ij} = -i\rho \psi^2 \delta_{ab},$$

$$\delta^a_{ij} \lambda^a_{k\ell} - \lambda^a_{ijk} \lambda^a_{j\ell} = \frac{2\epsilon}{\sigma_0}(\eta_{ij} \eta_{kl} + \eta_{ik} \eta_{j\ell} - 2\eta_{ki} \eta_{j\ell}), \quad \sigma_0 = 2(d + \epsilon)/C_\rho,$$

(2.2)

and the quadratic nonlinearity is defined by $(JJ)(\omega) := \frac{1}{2\pi i} \oint d\zeta J^i(\zeta)J^j(\omega)/(\zeta-\omega)$. The Cartan-Killing metric $g^{ab}$ is defined as: $g_{ab} = f_{ac} f_{bd}^c = -C_\rho \delta_{ab}$. The Lie algebra is taken to be complex for the time being. The Dynkin index $i_\rho$ of the representation $\rho$ is defined by $i_\rho = \frac{dC_\rho}{D\psi^2}$, where $C_\rho$ is the eigenvalue of the second Casimir in the representation $\rho$ defined by $\lambda^a_{ij} \lambda^k_{a} = -C_\rho \delta^a_{ij}$ and $\psi^2$ is the square of the longest root. (We adopt a convention in which the shortest root squared is 2 for all the Lie algebras). The central extension in the affine Lie algebra is parametrized such that the unitary highest weight representations exist for positive integer

2. BRST Operator for the Quadratically Nonlinear Superconformal Algebra

The algebras of the type listed in the Table are generated by the energy-momentum tensor $T(z)$, the dimension 3/2 supercurrents $G^i(z), i = 1, \ldots, \dim \rho := d$ and the dimension 1 currents $J^a(z), a = 1, \ldots, \dim g := D$. The products $T(z)T(\omega)$, $T(z)G^i(\omega)$ and $T(z)J^a(\omega)$ are standard. The remanining part of the operator product algebra takes the form

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(2.1a)

$$J^a(z)G^i(\omega) = \frac{-\lambda^i_a G^i(\omega)}{(z-\omega)} + \cdots,$$

(2.1b)

$$J^a(z)J^b(\omega) = \frac{-\frac{1}{2} \eta^{ab} \delta^2}{(z-\omega)^2} + \frac{f^{abc}J^c(\omega)}{(z-\omega)} + \cdots,$$

(2.1c)

where the generators $\lambda^a_{ij}$ and the structure constants $f^{abc}$ satisfy the relations [4]

$$\lambda^a_{aij} \lambda^k_{bj} - \lambda^a_{bjk} \lambda^k_{aij} = f^{abc} \lambda^c_{ij}, \quad \lambda^a_{aij} \lambda^b_{ij} = -i\rho \psi^2 \delta_{ab},$$

$$\delta^a_{ij} \lambda^a_{k\ell} - \lambda^a_{ijk} \lambda^a_{j\ell} = \frac{2\epsilon}{\sigma_0}(\eta_{ij} \eta_{kl} + \eta_{ik} \eta_{j\ell} - 2\eta_{ki} \eta_{j\ell}), \quad \sigma_0 = 2(d + \epsilon)/C_\rho,$$

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values of $k$. $C_v$ is the eigenvalue of the second Casimir in the adjoint representation of $g$ related to the dual Coxeter number $h^\vee_g$ by $C_v = \psi^2 h^\vee_g$. The raising and lowering of the indices $i, j, ..$ is done by the metric $\eta_{ij} = -\epsilon \eta_{ji}$, satisfying the relation $\eta_{ik} \eta^{jk} = \delta_l^j$, by the rule: $V^i = \eta^{ij} V_j$ and $V_i = \eta_{ij} V^j$, for any quantity $V$. The parameter $\epsilon = -1$ for the superconformal algebras and $\epsilon = +1$ for the quasisuperconformal algebras. For $\epsilon = -1$ the currents $G^i(z)$ are fermionic, while for $\epsilon = +1$ they are bosonic.

The tensor $P_{ij}^{ab}$ is defined by

$$P_{ij}^{ab} = \lambda_i^a \lambda^{bk}_{\ j} + \lambda_i^b \lambda^{ak}_{\ j} + \frac{2}{\sigma_0} \eta_{ji} \delta^{ab} \ .$$

Note the symmetry properties: $P_{ij}^{ab} = -\epsilon P_{ji}^{ab}$ and $\lambda_i^a = \epsilon \lambda^a_{ji}$. Thus $\eta^{ij} \lambda^a_{ji} = 0$. The OPE algebra (2.1) closes provided that the parameters occurring in the algebra obey the following relations [4]

$$\gamma = \frac{d(d + \epsilon)}{\psi^4 D_i \rho \eta} \ , \quad \sigma = \frac{2d}{\psi^2 D_i \rho \eta} [(d + \epsilon)(k + h^\vee_g) - D_i \rho] \ , \quad \gamma = \frac{3k \psi^2 \sigma + k(D + \epsilon \rho + 1)}{\eta} \ , \quad b = \frac{k \psi^2 \sigma}{2} \ ,$$

where

$$\eta = k + h^\vee_g + \epsilon \rho \ . \quad (2.6)$$

We now turn to the construction of the BRST operator corresponding to the above algebra. We introduce the pairs of ghosts $(b, c)$, $(\beta^i, \gamma^i)$ and $(r^a, s_a)$, corresponding to the generators $T, G^i$ and $J^a$, respectively. The ghosts $(c, \gamma^i, s^a)$ have ghost number 1 and conformal dimension $(-1, -\frac{1}{2}, 0)$, respectively, while the antighosts $(b, \beta^i, r^a)$ have ghost number $-1$ and conformal dimension $(2, \frac{3}{2}, 1)$, respectively. They satisfy the following OPEs:

$c(z)b(\omega) = (z-\omega)^{-1} + \cdots, \gamma^i(z)\beta^j(\omega) = \delta^i_j(z-\omega)^{-1} + \cdots, s^a(z)r^b(\omega) = \delta^{ab}(z-\omega)^{-1} + \cdots$

Using the result of [10] we make an ansatz for the BRST operator depending on a number of parameters. We then verify fully the nilpotency of the BRST operator, which fixes all these parameters and in addition imposes conditions on the parameters of the algebra (2.1). For the BRST operator we find the following result:

$$Q = cT + \gamma^i G_i + s^a J_a + bc \partial c + b \gamma^i \gamma_i + \lambda_{ai} \ (e - \frac{1}{2} \sigma_0 r^a \gamma^i \partial \gamma_i + s^a \beta^i \gamma_j) - \frac{1}{2} \epsilon^{abcd} r^c s^a s^b$$

Using the relations (2.5a,b) and various group theoretical relations provided in [5], we find that the above BRST operator is nilpotent provided that the central extensions satisfy the following relations:

$$k = -2(h^\vee_g + \epsilon \rho) \ , \quad c = 26 + 11 \epsilon \rho + 2D \ , \quad b = 16 + 6 \epsilon \rho \ . \quad (2.8a, b, c)$$
In (2.8b) the central charge equals the sum of contributions $2(-1)^{2s}(6s^2 - 6s + 1)$ from each generator of conformal dimension $s$ with an additional factor of $-\epsilon$ for spin $3/2$ generator. The relations (2.8b,c) agree with (2.5c,d), upon the use of (2.8a) and particular values of various group theoretical quantities listed in the Table. The crucial new information implied by the existence of the quantum BRST operator is the condition (2.8a) on the affine Lie algebra level $k$. From the Table we see that $k$ will always be negative (for $N > 4$). This is potentially a problem in obtaining unitary representations of the algebra.

For the special case of $SO(N)$–extended superconformal algebras, the level $k$ and the Virasoro central extension $c$ are [10]

$$ k = 6 - 2N, \quad c = 26 - 12N + N^2. \quad (2.9) $$

Note that once we restrict ourselves to the region $N > 4$, we have $c > 0$ for $N \geq 10$. Furthermore, $c < 0$ for the cases $g = B_3$ and $g = G_2$. It should be emphasized, however, that so far we have considered the complex form of the Lie algebra $g$. In applications, it is useful to consider its real forms. For example, for $D_n$, the real forms are $so(2n)$, $so(p,q)$, $(p = q = 2n)$ and $so^*(2n)$. Using the noncompact real forms, and imposing an invariance condition under their maximal compact subalgebras, one may in principle obtain unitary representations. The implications of such a construction remains to be seen.

In ref. [9], we also found the conditions for the existence of nilpotent BRST operator for quadratically nonlinear superconformal algebras whose current algebra sector is based on $osp(N|2M)$ or $s\ell(N + 2|N)$. In the former case, the conditions on $k$ and $c$ are exactly of the form given in (2.9) but with $N$ replaced by the superdimension $d_s \equiv N - 2M$, while in the latter case we found that $k = -4$ and $c = -12$.

### 3. Free Field Realisation of Quadratically Nonlinear Superconformal Algebras

The first free field realisation of a quadratically nonlinear algebra to be constructed was that of $SO(N)$–extended superconformal algebra in terms of $N$ real fermions $\psi_i(z)$ and a real boson $\phi(z)$ [13]. This realization has level $k = 1$ and therefore is not suitable for the BRST operator. This realisation was later generalized for arbitrary level $k$ for the case of $SO(N)$ and $SU(N)$–extended superconformal algebras in ref. [11] and to all the algebras listed in table in ref. [14]. For a physical application the $SO(N)$–extended algebra seems to be the most promising at present, and therefore here we shall consider the realisation of this particular case only.

The $SO(N)$–extended superconformal algebra is realised in terms of a real scalar $\phi$ with a background charge $\alpha$, $N$ real fermions $\psi^i$ and level $\ell$ affine Lie algebra currents $K^a$. The
generators of the algebra are realised in terms of these fields as follows [11]

\[
T = - \alpha \partial^2 \phi - \frac{1}{2} \partial \phi \partial \phi - \frac{1}{2} \psi \partial \psi - \frac{1}{2 \eta} K^a K_a,
\]
\[
G_i = 2 i \alpha \partial \psi + i \partial \phi \psi - 2 i \alpha \ell^{-1} \lambda^a_{ij} K_a \psi^j,
\]
\[
J_a = K_a + \frac{1}{2} \lambda^a_{ij} \psi^i \psi^j.
\]

These generators obey the algebra (2.1) with \( b, c, \gamma, \sigma \) given in (2.5) evaluated for \( SO(N) \) and provided that the following additional relations hold [11]

\[
k = \ell + 1 , \quad \alpha^2 = \frac{\ell^2}{4 \eta} .
\]

The value of the central charge can be written a way which illustrates the contribution of different terms in the energy momentum tensor as follows

\[
c = 1 + 12 \alpha^2 + \frac{N}{2} + \frac{\ell D}{\eta} .
\]

The existence of the quantum BRST operator imposes the restriction \( k = 6 - 2N \) which in turn restricts the value of the background charge to be

\[
\alpha = \frac{2N - 5}{2 \sqrt{3} - N} .
\]

Note that for \( N > 4 \) the background charge becomes imaginary. The free field realisation of the level \( \ell \) currents \( K^a \) can be achieved by the Wakimoto construction [15] which uses \( N/2 \) free scalars and additional commuting fermionic fields. The \( N/2 \) free scalars do not seem to lend themselves to a spacetime interpretation. The real challenge is to find a multi-scalar realisation which will allow such an interpretation.

4. A Nonlinear Superconformal Algebra Based on \( S^7 \)

A characteristic feature of the algebras that we have considered so far is that the OPE of the two spin 3/2 currents contains an operator bilinear in spin 1 currents. In this section we will discuss an \( N = 8 \) nonlinear superconformal algebra based on seven-sphere \( S^7 \) [12] which is a different type of nonlinear algebra. It is a soft algebra because its structure ‘constants’ are not constants but depend on a point of the seven-sphere. A certain version of this algebra arises in a twistor-like formulation of \( D = 10 \) dimensional Green-Schwarz superstring as a symmetry on the world-sheet [16], and the current algebra sector was constructed sometime ago [17]. The algebra constructed in ref. [12] contains the energy-momentum tensor \( T \), fermionic dimension 3/2 operators \( G^a \), \( (a = 0, 1, ..., 7) \), and a multiplet of spin 1 currents \( J^i \).
(i = 1, 2, ..., 7). The structure functions of the algebra depend on the coordinates of seven sphere parametrized by unit length octonions X. Namely, \( S^7 = \{ X \in \mathbb{O} \mid |X| = 1 \} \). We can express X as \( X = X^a e_a = X^0 e_0 + X^i e_i \) where the octonionic units are \( e_a = (1, e_i) \) and \( e_i \) obey the algebra \( e_i e_j = -\delta_{ij} + c_{ijk} e_k \) where \( c_{ijk} \) are the octonionic structure constants. Octonionic conjugation is defined as \( X^* = X^0 e_0 - X^i e_i \). Using the notation of ref. [12], we define \( [X] = \frac{1}{2} (X + X^*) \) and \( \{ X \} = \frac{1}{2} (X - X^*) \).

The construction of the algebra of ref. [12] proceeds by setting \( X = \lambda/|\lambda| \) and introducing the real scalar fields \( \phi^I (I = 0, \ldots, 7) \), the anticommuting fermions \( S^a \), bosons \( (\lambda^a, \omega^a) \) with conformal weights \( (1/2, 1/2) \), and their anticommuting superpartners \( (\theta^a, \pi^a) \) of conformal weights \( (0, 1) \). (While \( \phi^I \) and \( S^a \) are candidates for the bosonic and fermionic coordinates of a target superspace, the interpretation of the other fields is less clear. They may arise in a twistor-like formulation of superstring theory). In terms of these fields the generators of the algebra are represented as follows [12]

\[
J^i = -\Gamma^i_{ab} (1) \omega^a \lambda^b - \frac{1}{2} \Gamma^i_{ab} (X) S^a S^b ,
\]

\[
G_a = c_{abc} (1) (\pi^b \lambda^c - \partial \theta^b \omega^c) + \frac{1}{2} \Gamma_{ab} (X) \partial \phi^I S^b - t_{abcd} (X) |\lambda|^{-1} \partial \theta^b \omega^c \partial S^d ,
\]

\[
T = \frac{1}{2} (\partial \lambda^a \omega_a - \lambda^a \partial \omega_a) - \pi^a \partial \theta_a + \frac{1}{2} \partial \phi^I \phi^I - \frac{1}{2} S^a \partial S_a ,
\]

where

\[
\Gamma^i_{ab} (X) = \left[ (X e_a)^* (X e_b) e_i \right] , \quad \lambda^I_{ab} (X) = \left[ ((X e_I)^*) (X e_b) e_i \right] , \quad c_{abc} (X) = \left[ ((X e_b)^*) (X e_c) e_i \right] , \quad t_{abcd} (X) = (\delta^{fb} - X^f X^b) \left[ ((X e_c)^*) (e_f e_d) e_i \right] .
\]  

(4.1)

Using the two point functions implied by the form of the energy-momentum tensor, and keeping only the single contraction terms, which amounts to the calculation of the \textit{classical} algebra, for the nontrivial part of this algebra one finds [12]

\[
J_i (z) J_j (\omega) = \frac{2}{(z - \omega)} c_{ij} (X) J_k + \cdots ,
\]

\[
J_i (z) G_b (\omega) = \frac{1}{(z - \omega)} \left( \tau^i_{ab} (X) G^b (\omega) + \lambda_{ijabc} - \tau_{ijabc} (X) \right)|\lambda|^{-2} \partial \theta^c \omega^j + \cdots ,
\]

\[
G_a (z) G_b (\omega) = - \frac{2}{(z - \omega)^2} \Gamma^i_{ab} (X) J_i (\omega) - \frac{1}{(z - \omega)} \left( \Gamma^i_{ab} (X) \partial J_i (\omega) + 2 \delta_{ab} T (\omega) \right) + \cdots ,
\]

where

\[
\tau^i_{ab} (X) = \left[ ((e_a X^*) (X e_i)) e_b \right] ,
\]

\[
\lambda_{ijabc} = \left[ (e_b^* ((e_c e_a) e_i)) e_j \right] ,
\]

\[
\tau_{ijabc} (X) = \left[ (e_b^* (e_c ((e_a X^*) (X e_i)))) e_j \right] .
\]  

(4.2)

(4.3)

(4.4)
The quantum version of this algebra is not known. However, the quantum version of the $S^7$ loop algebra and the Sugawara construction based on it has been discussed in [18]. A classical BRST operator associated with the $S^7$ loop algebra is also given in ref. [18].

5. Conclusions

If the quadratically nonlinear superconformal algebras are to find applications in the construction of a new type of string theory, there are two main obstacles that need to be overcome. Firstly, a multi-scalar realisation that will allow a spacetime interpretation needs to be found. Secondly, the issue of unitarity needs to be addressed since the existence of quantum BRST operator fixes the level of the affine Lie algebra sector to be negative. Taking the affine Lie algebra sector to be based on a noncompact Lie algebra and then imposing an invariance condition under its maximal compact subalgebra may provide a solution. Whether this is indeed the case and the implications of such a construction as far as spacetime interpretation is concerned remains to be seen.

Finally, an alternative way of going beyond local $N = 4$ worldsheet supersymmetry in string theory may be based on far more nonlinear extended superconformal algebras, one of which is due to ref. [12], as described in the last section. Another example may be provided by the $N = 8$ conformal supergravity of ref. [19].
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