Personal recollections of the early days before and after the birth of Supergravity

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- March 29, 1976: Dan Freedman, Sergio Ferrara and I submit first paper on Supergravity to Physical Review D.
- April 28: Stanley Deser and Bruno Zumino: elegant reformulation that stresses the role of torsion.
- June 2, 2016 at 1:30pm: 5500 papers with Supergravity in the title have appeared, and 15000 dealing with supergravity.
- Supergravity has
  - led to the AdS/CFT miracle, and
  - made breakthroughs in longstanding problems in mathematics.
- Final role of supergravity? (is it a solution in search of a problem?)
- 336 papers in supergravity with 126 collaborators
- Now: many directions I can only observe in awe from the sidelines

I will therefore tell you my early recollections and some anecdotes. I will end with a new research program that I am enthusiastic about.

In 1972 I was a Joliot Curie fellow at Orsay (now the Ecole Normale) in Paris. Another postdoc (Andrew Rothery from England) showed me a little book on GR by Lawden.[1] I was hooked. That year Deser gave lectures at Orsay on GR, and I went with him to Brandeis.

In 1973, 't Hooft and Veltman applied their new covariant quantization methods and dimensional regularization to pure gravity, using the 't Hooft lemma (Gilkey) for 1-loop divergences and the background field formalism of Bryce DeWitt. They found that at one loop, pure gravity was finite:
$\Delta\mathcal{L} \approx \frac{1}{\epsilon}\left[\alpha R_{\mu\nu}^2 + \beta R^2\right] = 0$ on-shell. But what about matter couplings?

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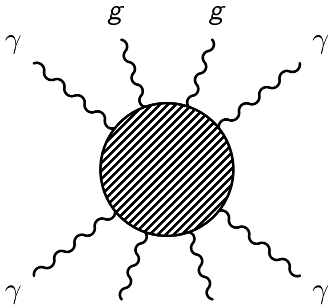
[1] "An Introduction to Tensor Calculus and Relativity". It is excellent, and I still use it in my classes.

1974

- Einstein-Maxwell system: 1-loop nonrenormalizable
- Einstein-Dirac system: 1-loop nonrenormalizable
- Einstein-QED system: 1-loop nonrenormalizable (with Deser, Tsao, Grisaru, Pendleton, C.C. Wu)
- What next? I wondered about conformal (Weyl) gravity; Veltman and Salam suggested studying spin 3/2



$$\Delta\mathcal{L} = \frac{1}{\epsilon}\frac{137}{60}(R_{\mu\nu})^2 \neq 0$$

$$g_{\mu\nu} \to g_{\mu\nu} + \kappa h_{\mu\nu}$$

$$\mathcal{L}_{\text{fix}} = -\frac{1}{2}\sqrt{-g}(h_\mu - D_\mu h)^2 - \frac{1}{2}\sqrt{-g}(D_\mu A^{\mu a})^2$$

- Summer 1974: I met Dan at the Paris Summer Institute.
- Fall 1975: I became assistant professor at Stony Brook. Dan had studied rigid susy with Bernard de Wit, and I had studied spinors in GR, so he proposed we collaborate on a gauge theory of supersymmetry. ("The right people at the right place at the right time")
- Sergio met Dan in Paris that Fall and joined.

Many ups and downs followed.

- Noether current for local supersymmetry,
- Schouten identity,
- canonical quantization of Majorana fermions only in particular frame.
- "In heaven there is no beer, that's why we drink it here."
- "Supergravity is dead/supergravity is alive"

We used the contorsion tensor of Hehl, which led to a point where a Fortran calculation of the integer coefficients of about 1000 spinor structures (6 spinors : $\bar{\epsilon}\psi\bar{\psi}\psi\bar{\psi}\psi$) had to be evaluated. All coefficients had to vanish. Success, Postnatal Depression.

Since this was a brand-new theory, we had to follow the same investigations as in the early days of O(ordinary)QFT. That taught me a lot about OQFT (and respect for the giants of 1925-1935).

The new theory was a treasure trove

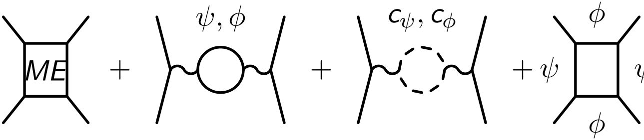
1976
- gauge algebra of local susy (with Dan)
- Maxwell-Sugra (with Sergio, Scherk)
- WZ-Sugra (with Breitenlohner, Sergio, Dan, Gliozzi, Scherk)
- Extended $\mathcal{N} = 2$ Sugra (with Sergio)
  $(2, 3/2) + (3/2, 1)$: "Einstein's dream"
- Gauged supergravities (Dan)
- Super Λ (Townsend)
- The $\mathcal{N} = 8$ sugra (Cremmer, Julia)
- Gauged $\mathcal{N} = 8$ sugra (de Wit, Nicolai)

1977
- Conformal $\mathcal{N} = 1$ sugra (with Kaku, Townsend)
- its $\mathcal{N} \leq 4$ bound (with Sergio, Kaku, Townsend)

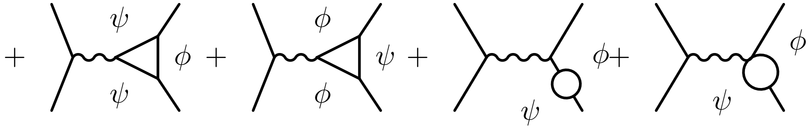
Then I went back to 1-loop studies

1976
- Maxwell-Einstein Sugra is **not finite**
- WZ-Einstein Sugra is **not 1-loop finite**
- $\mathcal{N}=2$ Sugra is **1-loop finite** !! (with Vermaseren and Grisaru)
- $\mathcal{N}=1$ Sugra is **2-loop finite** !! (Grisaru)

Divergences in photon-photon scattering in $\mathcal{N}=2$ Sugra



$$\frac{137}{60} \quad + \quad \left(2\times\frac{23}{120}\right) \quad + \quad (2\times 0) \quad + \quad (-1)$$



$$+ \quad \left(-\frac{5}{6}\right) \quad + \quad \left(-\frac{5}{6}\right) \quad + \quad 0 \quad + \quad 0 = 0$$

Dear Peter,

The following are finite despite no standard symmetry arguments predicting it:

- Pure half maximal sugra in $d = 5$ at 2 loops `1209.2472`
- Pure $d = 4, \mathcal{N} = 4$ sugra at 3 loops `1202.3424`
- Pure $d = 4, \mathcal{N} = 5$ sugra at 4 loops `1409.3089`

There are divergences in $d = 4, \mathcal{N} = 4$ sugra at 4 loops but it appears to be connected to an anomaly in the duality symmetry. `1309.2498`

$\mathcal{N} = 8$ is predicted to diverge at 7 loops, but I expect it to be finite.

Best wishes,
Zvi

Further developments

1977
- BRS(T) introduced into (super)gravity (with Townsend)
  T from Lebedev
- Finiteness of $\mathcal{N}=3$ and $\mathcal{N}=4$ Sugra at 1-loop (with Vermaseren)

1978
- Unitarity of Sugra from cutting rules of Veltman:
  4-ghost couplings needed. (with Sterman, Townsend)
- Auxiliary fields of $\mathcal{N}=1$ Sugra (with Sergio)
  (also: Stelle-West). They explained the 4-ghost couplings.

1978
- The gravitational axial anomaly (with Grisaru, Dan).
  First Christensen, Duff. (Later with Grisaru, Römer, Nielsen)
  New ghosts needed: NK ghosts.

1978
- Tensor calculus (with Sergio)
  Based on Conformal Sugra. "Simplified Superspace".

1979
- (Super)Higgs without Λ
  (with Cremmer, Julia, Scherk, Sergio, Girardello)
  Follow-up with Van Proeyen

1980 • Siegel's dimensional regularization for supersymmetry by dimensional **reduction** ("ϵ-scalars" with Capper, Jones).

1980 • Quantization of $A_{\mu\nu\rho\ldots}$: unusual ghost counting (with Sezgin)

1981 • no Λ in $d = 11$ (with Nicolai, Townsend)

1982 • **Local** BRST (with Ore). Who ordered that?

These were some of the highlights I contributed to in the first 6 years. But how was supergravity received in the wider world of physics?

How was supersymmetry/supergravity received?

We were young and did not know too much ("Knabenphysik", Pauli). But the establishment was hesitant, some frowned (except Salam, Yang, Weinberg). This did not help getting jobs...

> *...I am uninterested in gravity, and superuninterested in supergravity...*
>
> (S. Coleman)

Some tried:

> *After the year at CERN, I intended to continue working on supersymmetry and invited Martin Sohnius to come to Hamburg for some period. There was one obvious task: to arrive at a local version where the global fermionic charges were replaced by spinorial charge densities, possibly accompanied by some local fermionic gauge principle. We were not successful in this.*
>
> (R. Haag (of HLS))

My advisor is an implacable adversary:

> *The reader may ask why in this book [Facts and Mysteries of Elementary Particles, 2003] string theory and supersymmetry have not been discussed... The fact is that this book is about physics and this implies that theoretical ideas must be supported by experimental facts. Neither supersymmetry nor string theory satisfy this criterion. They are figments of the theoretical mind. To quote Pauli, they are not even wrong. They have no place here...*

(M. Veltman)

and others see supergravity as a threat:

> *By this criterion, QCD is a science. But can the same be said of superstrings and its ilk. . . Can it be argued that elegance, uniqueness, and beauty, define truth? . . . Perhaps I have overstated the case made by string theorists in defense of their new version of medieval theology where angels are replaced by Calabi-Yau manifolds. The threat, however, is clear. . .*

(S. Glashow, The Charm of Physics (1991))

My own point of view is this: There is nothing wrong with enthusiastically exploring new ideas in physics without initially worrying much about their mathematical rigor or experimental support. First of all: new ideas are better than any criticism. Secondly: if the ideas are wrong, these efforts will fade by themselves, and if they are right, they will need no justification.

Let me now turn to my new research topic, which is in collaboration with Robert Wimmer.

Solitons, Anomalies, Supercurrents and Supergravity

Many supersymmetric models have soliton solutions:

- kink in $\mathcal{N} = (1, 1), d = 1 + 1$
- vortex in $\mathcal{N} = 2, d = 2 + 1$
- monopole in $\mathcal{N} = 2, d = 3 + 1$ **and** in $\mathcal{N} = 4, d = 3 + 1$.

In each case $\{Q, Q\} = P + Z$, where
$Q = \int j^0 \; dx, \quad P^\mu = \int T^{\mu 0} \; dx; \quad Z = \int \mathrm{div}\, \vec{\zeta} \; dx.$

To compute quantum corrections in the presence of extended objects like solitons, we constructed a regularization scheme for these models that preserves supersymmetry: dimensional regularization by dimensional embedding (DRDE).

Idea: All models can be written as $\mathcal{N} = 1$ models in one (or two) higher dimensions. Begin with model in D dimensions, then use dimensional regularization by going down **all the way to d dimensions**. The extra dimension acts as a regulator. At all stages, supersymmetry is preserved. Rebhan, Wimmer, vN

(Using DRDR requires evanescent counterterms in currents, and $O(n-4)$ terms in the classical currents, see Grisaru and West for $\mathcal{N} = 1$, but if $d \leq 4$ solitons occupy all space.)

Results: For most models: $M^{(1)} \neq 0, Z^{(1)} \neq 0$, but $M^{(1)} = Z^{(1)}$: still BPS. There are various contributions at 1-loop:

- bulk ($\sum \frac{1}{2}\hbar\omega$: use index theorems for $\Delta\rho(k^2)$)
- boundary (evaluate using $r \to \infty$)
- renormalization (fix Z factors in "flat space")
- tadpole cancellations (even finite parts)
- composite operator renormalization.[2] (only for $\mathcal{N} = 4, d = 3 + 1$)

First hint at anomalies

Previous (naïve) calculations gave $Z^{(1)} = 0$. With supersymmetric regularization, $Z^{(1)} = \epsilon/\epsilon = \text{finite} \neq 0$. But P_μ, Q and hence Z do not have anomalies! It is a puzzle.

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[2] Recall that internal conserved currents do not renormalize, but $T_{\mu\nu} = T^{\text{imp}}_{\mu\nu} - \Delta T^{\text{imp}}_{\mu\nu}$, and $\Delta T^{\text{imp}}_{\mu\nu}$ (but not $T^{\text{imp}}_{\mu\nu}$) **does** renormalize. Same for supersymmetry and central charge currents.

Is $Z^{(1)}$ (pure) anomaly? (Wimmer, vN)
For kink, yes. For monopole?
Recall: A composite operator may not transform (under supersymmetry) by only transforming its constituent fields ("Konishi anomaly"). Also, $\gamma^\mu j_\mu$ is part of j^μ (just like $T_\mu{}^\mu$ is part of $T^{\mu\nu}$).

Strategy:

- Study abstract current and anomaly multiplets for $\mathcal{N} = 2, d = 3 + 1$. Determining the x-space components of multiplets for any particular model is hugely complicated. Lesson: study them in a model-independent way in superspace.
- Construct the explicit realization for $\mathcal{N} = 2$ SYM
- Compare with the 1-loop results for $M^{(1)}$ and $Z^{(1)}$.

Relation to supergravity:
Given a current multiplet, one can construct a corresponding sugra theory. Conversely, given an off-shell sugra, one can extract conformal current multiplets and anomaly multiplets. This way one arrives at

Classification of current/anomaly multiplets in $d = 3 + 1$:

- $\mathcal{N} = 1$: Kuzenko (recently Komargodski and Seiberg)
- $\mathcal{N} = 2$: less studied (Stelle, de Wit, Philippe, Van Proeyen, Kuzenko, Theisen, Butter, Magro, Sachs, Wolf). This is the case we are working on.

Abstract $\mathcal{N}=2$ current and anomaly multiplets:

1. $\mathcal{D}^{ij}\mathcal{J}=0$: conformal current multiplet $\big(i,j=1,2,\ \mathcal{J}^*=\mathcal{J}\big)$

$$\mathcal{J}=\{\underbrace{J;\chi^i_\alpha,\bar\chi_{\dot\alpha i};a_{\mu\nu}}_{\text{auxiliary}},\underbrace{j_\mu,j^{ij}_\mu}_{u(2)};\underbrace{\mathcal{J}^{\mu i}_\alpha,\bar{\mathcal{J}}^\mu_{\dot\alpha i}}_{\text{susy}};\underbrace{\theta_{\mu\nu}}_{\text{stress}}\}$$

   Consistency: conserved and "traceless"
   Example: classical $\mathcal{N}=2$ SYM

2. $\mathcal{D}^{ij}\mathcal{J}=4\hbar\mathcal{L}^{ij}\qquad(\mathcal{D}^{(i}_\alpha\mathcal{L}^{jk)}=0;\ (\mathcal{L}^{ij})^*=\mathcal{L}_{ij})$

$$\mathcal{L}^{ij}=\{\ell^{ij};\psi^i_\alpha,\bar\psi_{\dot\alpha i};\zeta^{\text{an}}_\mu;B,\bar B\}\qquad\text{with } \partial^\mu\zeta^{\text{an}}_\mu=0$$

$$\text{Consistency:}\ \left\{\begin{array}{rcl}\partial\cdot j&=&\hbar\,\mathrm{Im}\,B\\ T_\mu{}^\mu&=&-\hbar\,\mathrm{Re}\,B\\ (\bar\sigma\cdot\mathcal{J}^i)_{\dot\alpha}&=&\hbar\bar\psi^i_{\dot\alpha}\end{array}\right.$$

Supersymmetry transformation of currents:

$$\{Q^i_\alpha, \mathcal{J}^0_{\beta j}\} = - iD^i_\alpha \mathcal{J}^0_{\beta j}|$$
$$= \delta^i_j \epsilon_{\alpha\beta} \left(\frac{1}{3} \operatorname{div} \vec{\zeta} + \hbar \zeta^0_{\text{an}} \right) + (\sigma^{0k})_{\alpha\beta} \left(\frac{i}{2} \delta^i_j (\operatorname{rot} \vec{\zeta})_k + 2\hbar \partial_k \mathcal{L}^i{}_j \right)$$

$$\text{where } \vec{\zeta}^k = 4 \left(a^{k0} + \frac{i}{2} \epsilon^{kmn} a_{mn} \right).$$

Note that $\operatorname{div} \vec{\zeta}$ is the classical central charge, and
$\hbar \zeta^0_{\text{an}}$ is the anomaly contribution.

Explicit realization: $\mathcal{N} = 2$ SYM

$$\mathcal{J} = \mathrm{tr}\, W\bar{W}, \qquad \mathcal{L}^{ij} = b\left(\mathcal{D}^{ij}\,\mathrm{tr}\, WW + \bar{\mathcal{D}}^{ij}\,\mathrm{tr}\,\bar{W}\bar{W}\right)$$

with b not yet fixed.

$$a^{\mu\nu} = \mathrm{tr}\left(\mathrm{Re}\,\phi\ \tilde{F}^{\mu\nu} - \mathrm{Im}\,\phi\ F^{\mu\nu}\right)$$

$$\hbar Z^{\mu} = b\partial_{\nu}\left(\mathrm{tr}(\mathrm{Re}\,\phi\ \tilde{F}^{\mu\nu} + \mathrm{Im}\,\phi\ F^{\mu\nu}) + \lambda^{i}\sigma^{\mu\nu}\lambda + \bar{\lambda}_{i}\sigma^{\mu\nu}\bar{\lambda}^{i}\right)$$

We computed $Z^{(1)} = \int \langle \partial_k \zeta^k \rangle^{(1)}_{\mathrm{mono}}\ d^3x$ in Vienna.
Question: is $Z^{(1)} \stackrel{?}{=} \int \zeta^0_{\mathrm{an}}\ d^3x$?

We need to fix b: need $\mathcal{N} = 2$ supersymmetric regularization scheme. From $F\tilde{F}$!

The last 40 years I have studied problems in Supergravity and Quantum Field Theory. During all these years, I have struggled with many collaborators to understand, apply and extend these subjects. Endless travels to exotic places, always to meet the same set of physicists, late nights in old buildings, despair when calculations turned out wrong, confusion that turned after hard work into more confusion: it has been a wonderful time.
Let us hope that Nature is aware of our efforts.