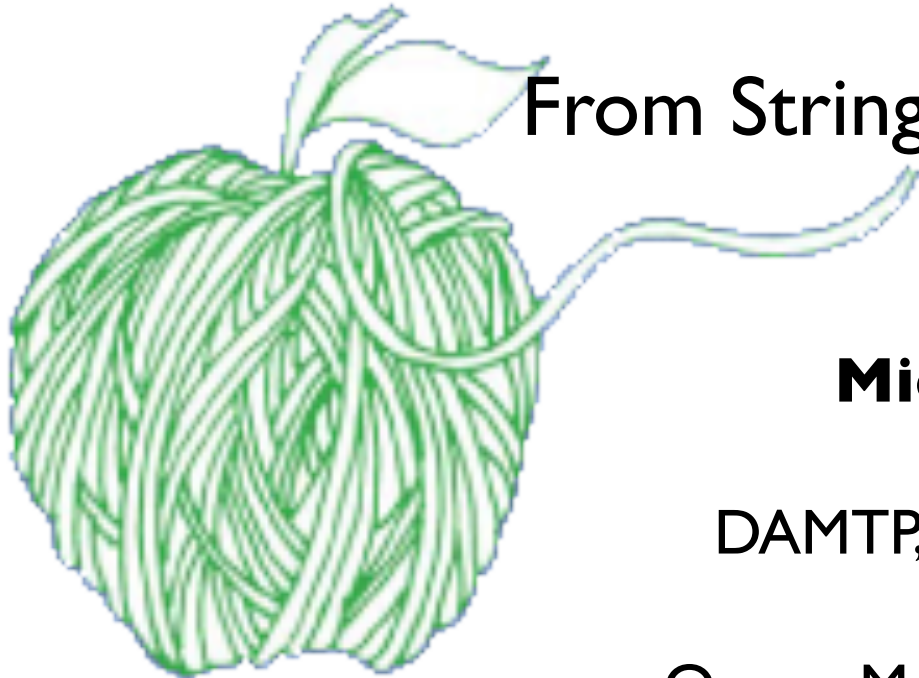


50 Years of the Veneziano Model

GGI Florence, May 11 - 15, 2007

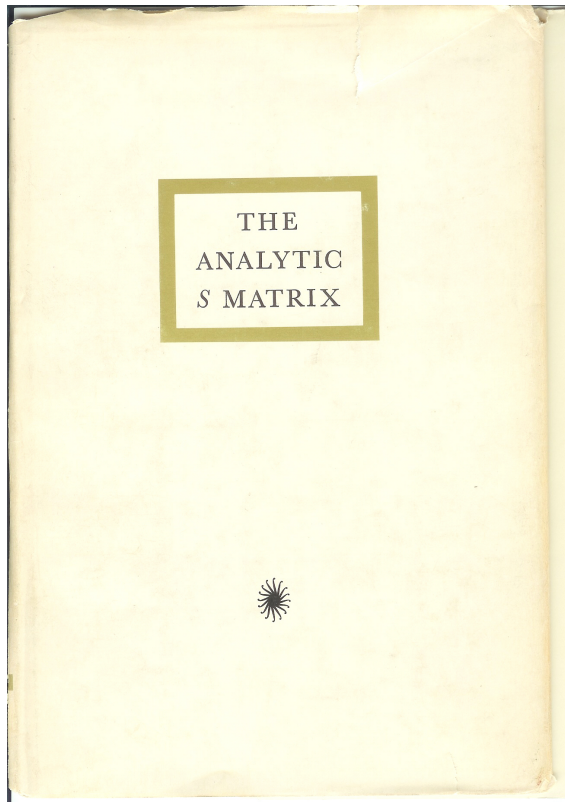
From Strings to Superstrings



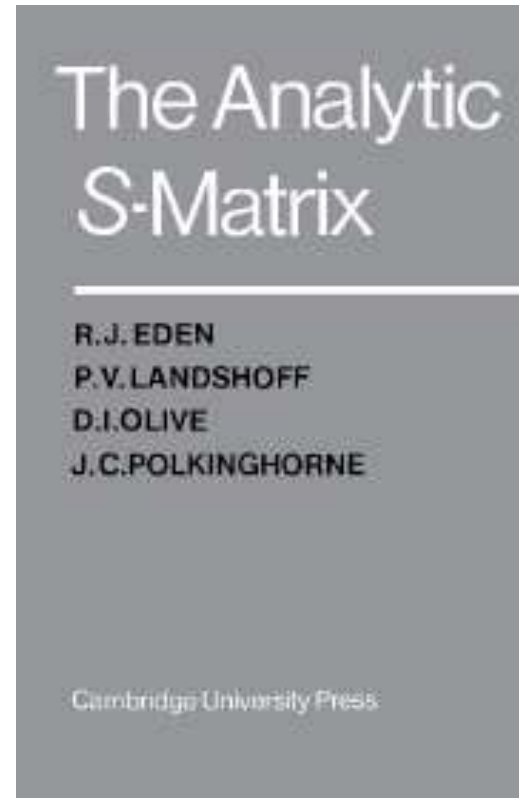
Michael B. Green

DAMTP, Cambridge University
and
Queen Mary University of London

Spot the difference!



G. Chew 1966



E.L.O.P. 1966

Immortal opening lines of the preface !! :
“One of the most remarkable discoveries in elementary particle physics has been that of the existence of the complex plane.”

1967 -1970 Graduate Student in Physics Dept., Cambridge

- There was no connection between General Relativity and Elementary Particles – pre String Theory, pre Hawking Radiation, Cosmology in its infancy.
- Apparent failure of quantum field theory (apart from QED)
-- no theory of the Weak or Strong forces
- The influence of S-MATRIX Theory of hadrons
The Bootstrap; Regge theory, Finite Energy Sum Rules; Narrow Resonances:

Out of this pre-1968 firmament emerged

THE VENEZIANO MODEL (1968)

The **PRIMORDIAL SOUP** that evolved into string theory

1970-76 A period of intense activity in developing string theory from dual models:
(SEE EARLIER TALKS)

- The no-ghost theorem and critical dimension.
- The fermionic dual models.
- From dual models to the string picture
- Properties of tree-level and loop scattering amplitudes
- Light-cone gauge string field theory
- Interpretation of string theory as a generalisation of gauge theory and of gravity.

Memorable conferences:

Remarkable dual models workshop Summer 1973 at CERN;;

Aspen Summer 1974 programme on dual models.

THIS WAS ALSO PERIOD OF : ASYMPTOTIC FREEDOM; STANDARD MODEL; 't HOOFT LARGE-N.

My own interests had focused on the possible rôle of the insertion of boundaries with DIRICHLET BOUNDARY CONDITIONS IN THE STRING WORLD-SHEET. These generate **off-shell currents and point-like fixed-angle scattering** – power behaved in energy. Could this relate to a string theory of hadrons ??

Recall fixed-angle scattering decreases exponentially with energy in conventional string perturbation theory - as noted in Veneziano's original paper.

Era of SUSY, SUGRA, Monopoles, Instantons, Kaluza-Klein,
diverted attention from string theory,

BUT NOTE: TWO KEY STRING THEORY DEVELOPMENTS OF 1976:

- **Brink, di Vecchia, Howe; Deser, Zumino** discovered the covariant (“**Polyakov**”) bosonic and fermionic actions.
- **Gliozzi, Scherk, Olive** showed that a suitable projection of the fermionic string spectrum possesses **Space-Time supersymmetry**.

[**CONFUSINGLY**, **GSO** performed an *inconsistent* **GSO** projection (!!)
leading to $N=1$ ten-dimensional open-string and closed-string theories **without RR sector** – anomalous. They should have discovered type II theories.]

JUST WHEN ALL THE INGREDIENTS WERE IN PLACE THERE WERE ESSENTIALLY NO
FURTHER STRING THEORY PAPERS FOR SEVERAL YEARS AFTER GSO!

Of course, there were many important developments in super Yang-Mills, supergravity,

- 11-dimensional supergravity (**Cremmer, Julia, Scherk (1978)**) and its compactifications.
- Formulation of $N=4$ super Yang-Mills (**Brink, Scherk, Schwarz (1977)**).

1979-84 CONSTRUCTION SUPERSTRINGS with Schwarz

1979. Summer at CERN

Met John Schwarz by chance in cafeteria and were both interested in investigating fermionic string. We studied $N=1$ SUSY Yang-Mills at one loop in $d=10$ and possible connection with string theory – we achieved rather little!

Decided to meet again in Aspen the following summer.

Many beautiful developments elsewhere:

Friedan, β function;

't Hooft, Anomaly matching;

Witten, Large N ;

Montonen, Olive, Witten, Osborn, $SL(2, Z)$ duality of $N=4$ Yang-Mills.

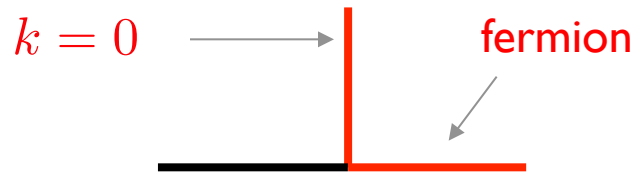
.....

.....

1980. Summer Aspen and St Andrews, Scotland

MAKING SPACE-TIME SUPERSYMMETRY MANIFEST.

- Identify the supercharge with **ZERO-MOMENTUM FERMION EMISSION**.



16-component chiral $SO(9,1)$ supercharge decomposes into two $SO(8)$ light-cone spinors

$$Q_a = \sqrt{p^+} S_a \quad Q_{\dot{a}} = \frac{1}{\sqrt{p^+}} (\gamma_i \cdot X^i S)_{\dot{a}}$$

New world-sheet superspace coordinates: triality of $SO(8)$:

$SO(8)$ vector X^i and $SO(8)$ fermionic spinor S_a

explicitly constructed out of the NSR world-sheet fields embodying GSO projection.

- Space-time supersymmetric version of the DDF states.

1981. Summer Aspen, Autumn Caltech

Very intense - two batchelors with time to spare.

- OPEN SUPERSTRING TREES AND LOOPS.
- FORMULATION OF TYPE II CLOSED SUPERSTRINGS
- CLOSED-STRING FOUR-GRAVITON ONE-LOOP AMPLITUDE. Modular invariance. The relation of tadpoles to divergences. Unlike bosonic case, type II superstring expression is **FINITE**
– remarkable for a ten-dimensional theory of gravity!!
- COMPACTIFICATION OF CLOSED-STRING LOOP (with **Brink**) from $d=10$ to $d=4$ on a torus. **$N=8$ SUPERGRAVITY LIMIT.** Introduction of the **lattice theta function of winding nos. and KK charges** – implementing modular invariance.

THE GEOMETRY OF STRING PERTURBATION THEORY, **Polyakov**;
Supersymmetry breaking, **Witten**;
Kaluza-Klein, **Witten**

1982. Summer Aspen, Autumn Caltech

- LIGHT-CONE GAUGE OPEN AND CLOSED SUPERSTRING FIELD THEORY.
(based on bosonic string **Mandelstam; Cremmer, Gervais**)
- FORMULATION OF TYPE IIB SUPERGRAVITY IN LIGHT-CONE
gauge (anticipated by **Nahm**'s classification but missed).

[Eventually formulated covariantly by **Schwarz; Howe, West.**]

1983. Autumn at Queen Mary, London

- A COVARIANT FORMULATION OF SUPERSTRING ACTION.

Need to interpret physical $SO(8)$ spinors S_a as half a covariant chiral (16-component) ten-dimensional spinor, Θ . Incorporates Siegel's κ -symmetry (Siegel's point superparticle).

Incorporates space-time supersymmetry, RR fluxes, ...

BUT covariant quantization is very (very!) subtle – no kinetic term for Θ .
c.f. Berkovits' Pure Spinor formalism.

- First (??) string conference December 1983 in Queen Mary.
- entire £120 budget spent on Gross.

Gravitational anomalies - absence of anomalies in type IIB Supergravity,
Alvarez-Gaume and Witten.

Self-dual even lattices and vertex operators ($E_8 \times E_8$, Spin $32/Z_2$) Goddard and Olive.

1984. Summer in Aspen.

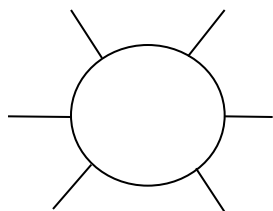
Type I (open superstring) theory anomaly calculation.

Many experts at Aspen in higher-dimensional supergravity program, in particular, **Bardeen, Zumino, Zee**; Non-abelian gauge and gravitational anomalies. **Friedan, Shenker**; BRST ghosts for strings; beta function for sigma models.

- In ten dimensions chiral gauge anomalies arise from hexagon diagrams with external gauge bosons or gravitons.
- Cancellation between the **ONE-LOOP** hexagon anomaly and an anomaly of a **TREE** diagram intermediate massless $C_{\mu\nu}$ (massless closed-string Ramond-Ramond state) exchange in **gravitational** sector.

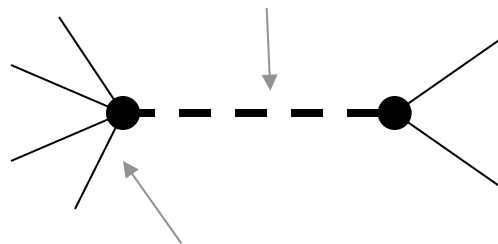
INTERPLAY OF GRAVITATIONAL AND GAUGE SECTORS.

Anomalous hexagon



+

Anomalous tree $C_{\mu\nu}$



= 0

new Chern-Simons vertex $C \wedge F^4$ or $C \wedge R^4$

- Chiral gauge anomalies vanishes for $SO(32)$ or $E_8 \times E_8$ gauge groups.
No independent 6th order Casimir of $E_8 \times E_8$ or $SO(32)$ IN VECTOR REP.
- Also gravitational anomalies cancel with matter fields
dimension of $SO(32)$ or $E_8 \times E_8 = 496$
- The $SO(32)$ open string is also finite at one loop (as was type II).

1984. Sep-Dec in Caltech. “STUFF HAPPENED”

- The content of my seminar at Aspen communicated to Princeton and **Witten** wrote his first string paper very quickly ($\sim c$) - almost before we had written our paper.
- We tried to formulate an $E_8 \times E_8$ superstring – **BUT** we lacked the bizarre insight that gave the **HETEROTIC STRING** (**Gross, Harvey, Martinec, Rohm**).
- We used Ricci-flat K3 manifold to compactify type I to six dimensions with $N=2$ SUSY - **BUT** we did not know about **CALABI-YAU THREEFOLDS** that were then used in the paper by **Candelas, Horowitz, Strominger, Witten** (which I received by **ZAP-MAIL**** at the 1984 Gainesville Christmas party!!)

1985. The world had changed –

Furthermore, John met Patricia – no longer batchelors with time to spare.

1986. Wrote a book with **Schwarz, Witten** - traumatic 6 months.
(new technology – internet, TeX, laser printers, ...)

A postscript:

1987-1995

Formulation of closed superstring version of Dirichlet boundary conditions;
Preserves $\frac{1}{2}$ supersymmetries;

BUT

1995

Polchinski developed the complete interpretation in terms of D-branes, leading to an understanding of non-perturbative stringy effects - Black Holes, AdS/CFT and much, much, more.

IT IS FITTING THAT MEMORY OF JOE POLCHINSKI, WHO CONTRIBUTED
SO MANY DEEP RESULTS, SHOULD END MY TALK