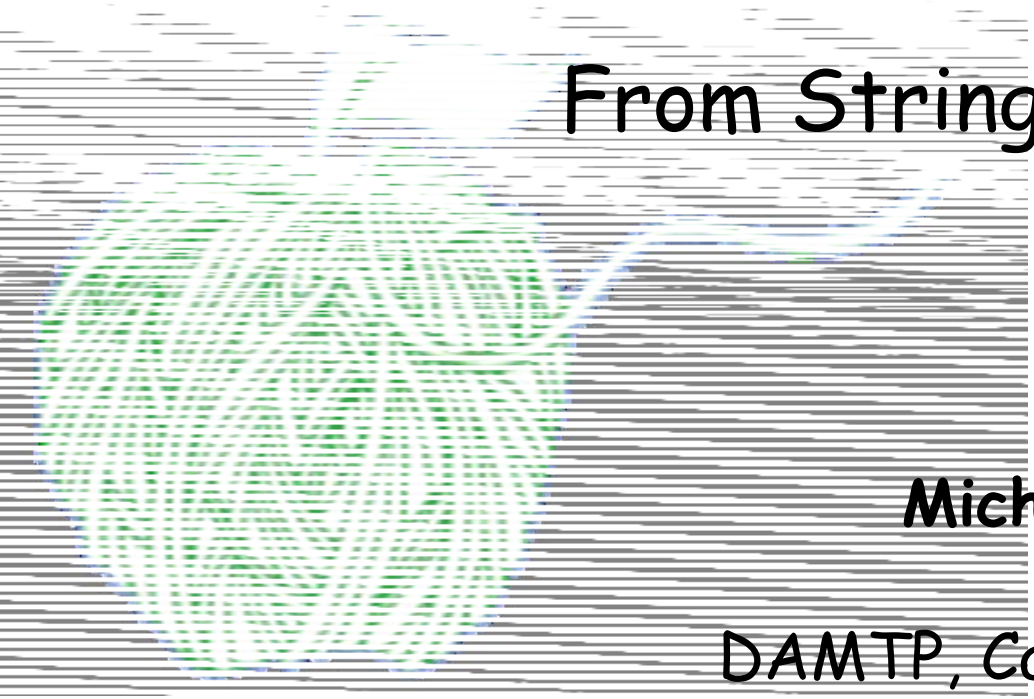
The Birth of String Theory

GGI Florence, May 18 - 19, 2007



From Strings to Superstrings

Michael B. Green

DAMTP, Cambridge University

1967 -1970 Graduate Student in Physics Dept., Cambridge

No interaction with Relativity - Cosmology was in its infancy.

Apparent failure of field theory

Even though this was the period in which Weinberg, Salam, and others were initiating the Standard Model !!

CHEWish influence: S-MATRIX Theory
The Bootstrap; Regge Theory

Esp. Remarkable prescience of Hagedorn (1965) who argued for an exponential density of states several years before String Theory embodied it.

Also Dirac (when he was 62 years old) had formulated the covariant action for a membrane with 3-dimensional world-volume in 1963, seven years before Nambu and Goto's string action.

THE ANALYTIC *S* MATRIX

The Analytic *S*-Matrix

R.J. EDEN
P.V. LANDSHOFF
D.I. OLIVE
J.C. POLKINGHORNE

Cambridge University Press

1967 - 1970

Regge theory, Hadronic phenomenology,
Finite Energy Sum Rules; Narrow Resonances:
Dolen, Horn, Schmidt;
Ademollo, Rubinstein, Veneziano, Virasoro;
Mandelstam;
Harari, Freund, Rosner;

VENEZIANO MODEL 1968

Factorization: Fubini, Veneziano; Bardakci, Halpern
Oscillator string: Nambu, Fairlie, Nielsen, Susskind
Geometric string: Nambu, Goto
Loops: Kikkawa, Sakita, Virasoro; Neveu, Scherk

1970-72 Postdoc at IAS, Princeton

Little contact with Princeton University group.
(Gross, Neveu, Scherk, Schwarz)

Phenomenology of duality for strong force. Also worked with Veneziano on resonance widths in a "bootstrap" approach to dual model.

Met Ramond with his fermions and Mandelstam, Thorn, Bardakci, Halpern, Virasoro and others in Berkeley.

Meanwhile: at CERN (Goddard, Rebbi, Thorn, Brink, Olive, Amati, Goldstone, Scherk , Corrigan, Lovelace,…)

at MIT (Di Vecchia, Del Giudice, Fubini, Veneziano, Brower, Weis, ..)

1973-78 Postdoc at Cambridge and Oxford

Summer 1973: CERN (Ramond, Olive, Amati, …)

Added fermion and boson loops – cancellation of tachyon singularity in loop! Would have presaged supersymmetric cancellations – but mistakenly ignored GSO projection !!

Remarkable CERN workshop: fermion vertex; loops; …
esp. (i) Seminar by Goldstone on l.c. string field theory, membranes and ???
(ii) Schwarz arrived with two manuscripts by Mandelstam on light-cone gauge scattering amplitudes.

Also: Large-N 'tHooft; Asymptotic Freedom; Standard Model

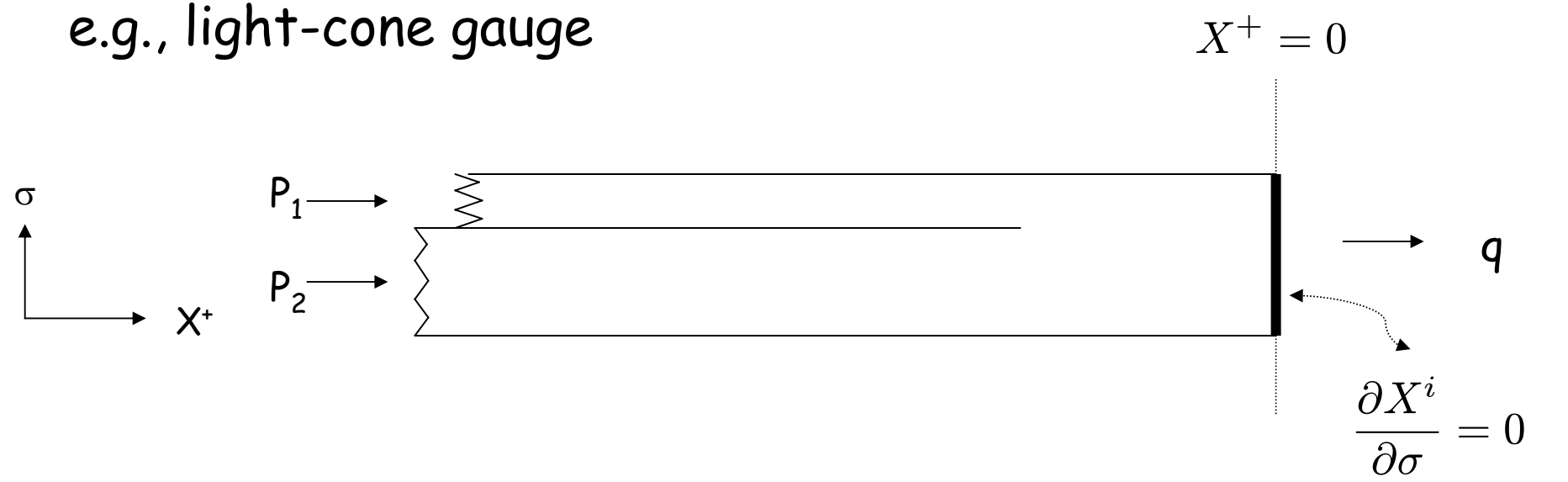
Interpretation as theory of gravity
Yoneya (1973); Scherk, Schwarz (1974)

Hadronic strings must couple to currents (off-shell).
Big puzzle that resisted many attempts.

Off-shell currents
c.f. Schwarz; Corrigan and Fairlie (1974)

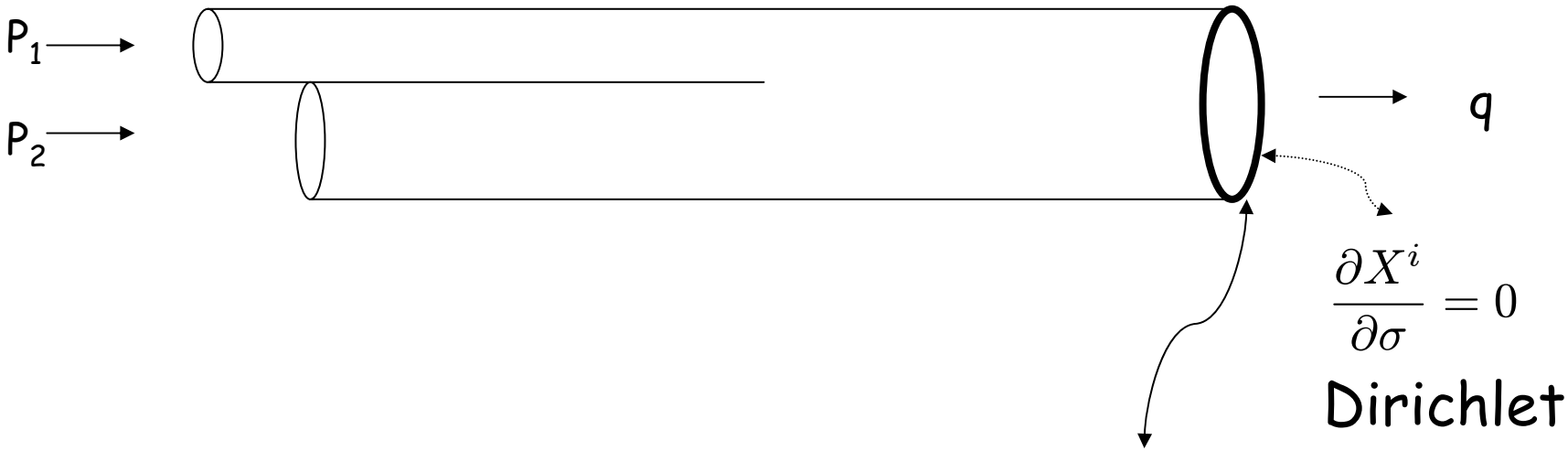
Dirichlet boundaries for open strings (1975).

e.g., light-cone gauge



Apparent inconsistencies between covariant expression
And light-cone gauge expression.

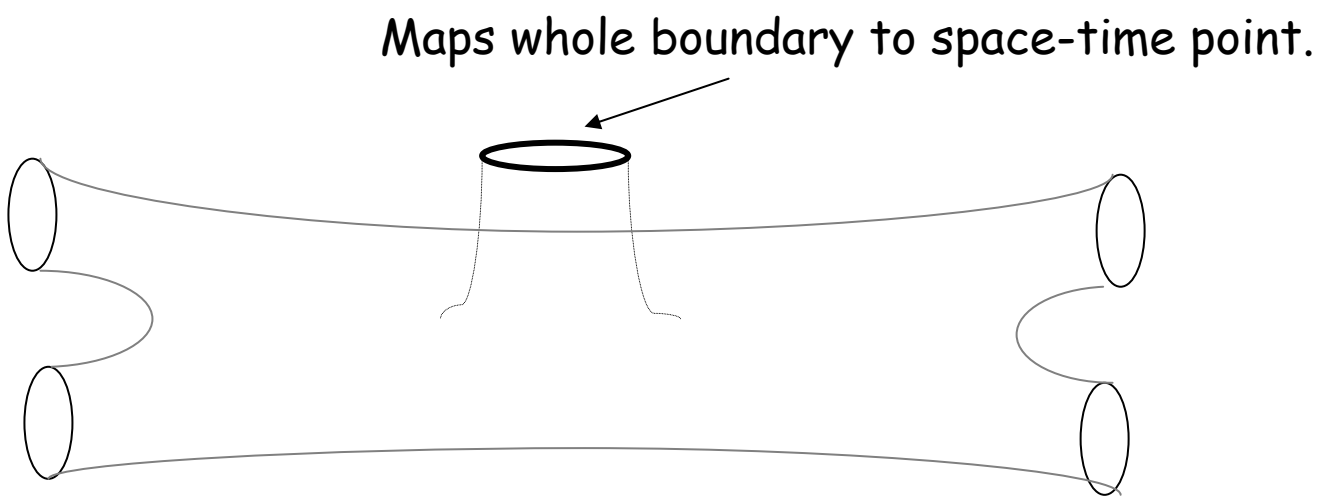
Dirichlet for closed strings ("D-instantons" nowadays) with Shapiro (1976). Closed-string form factor in bosonic and fermionic strings.



Boundary state satisfies $(L_m - \tilde{L}_{-m})|B\rangle = 0$

(where L_m are Virasoro operators).

World-sheet disk amplitude $= \langle 1, 2|B\rangle$



Zero momentum ~ Vacuum expectation value

Fixed-angle scattering is point-like in presence of Dirichlet boundaries. Hadronic phenomena ??
[Fixed-angle scattering decreases exponentially with energy in conventional string pert. theory.]

Insertion of Dirichlet boundaries reincarnated in modern developments in the form of D-INSTANTONS

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

BUT Two key 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 anomalous N=1 ten-dimensional open-string and closed-string theories (without RR sector). They should have discovered type II theories.

Just when all the ingredients were in place there were essentially NO FURTHER STRING THEORY PAPERS !!

Many important developments in supergravity, esp.

11-dimensional supergravity Cremmer, Julia, Scherk (1978)

1979-84 CONSTRUCTION OF SUPERSTRING with Schwarz

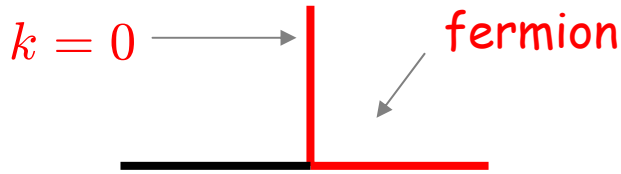
1979 Summer at CERN

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 connection with string theory – we achieved rather little.
Decided to meet again in Aspen the following summer.

Beautiful developments elsewhere:
Friedan, β funtion;
't Hooft, Anomaly matching;
Witten, Large N;
Montonen, Olive, Witten, Osborn, SL(2,Z) duality of N=4 Yang-Mills.

1980. Summer Aspen, St Andrews

Manifest space-time supersymmetry. The supercharge is identified with zero-momentum fermion emission.



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

$$Q^a \sim S^a \qquad Q^{\dot{a}} \sim \Gamma_i^{\dot{a}a} \partial X^i S^a$$

New world-sheet superspace coordinates:

SO(8) vector X^i and SO(8) spinor S^a

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

Triality of SO(8): $(X^i, \psi^i) \to (X^i, S^a)$

We decided to resume work together the following year.

1981. Summer Aspen, Autumn Caltech

Very intense (two batchelors with time to spare).

Papers:

(i) Open-string trees with manifest space-time SUSY.

(ii) Open-string loops.

(iii) Closed-string four-graviton loop. Modular invariance. The relation of tadpoles to divergences. [Error in Shapiro's beautiful 1971 bosonic string paper.] Unlike bosonic case, superstring expression was FINITE - remarkable for a ten-dimensional theory of gravity!!

(iv) With Brink. Compactification of closed-string loop from d=10 to d=4 on a torus. N=8 supergravity. Introduction of the lattice of winding nos. and KK charges, $\Gamma_{1,1}$ - modular invariance.

The geometry of string theory, Polyakov;
Supersymmetry breaking, Witten;
Kaluza-Klein, Witten

1981. Summer Aspen, Autumn Caltech
Very intense (two batchelors with time to spare).

(i) Open-string trees with manifest space-time SUSY

(ii) Open-string loops

(iii) Closed-string four-graviton loop. New issues to do with modular invariance. The relation of tadpoles to string divergences. [Note error in Shapiro's beautiful 1971 bosonic string paper.] Unlike the bosonic case superstring expression was FINITE!!

(iv) With Brink. Compactification of closed-string loop from d=10 to d=4 on a torus. N=8 supergravity. Introduction of the lattice of winding nos. and KK charges, $\Gamma_{1,1}$ - modular invariance.

We decided to resume work together the following year.

1982. Summer Aspen, Autumn Caltech

We thought that string field theory (generalizing conventional field theory) might be a more fundamental starting point.

(i) Light-cone gauge open superstring field theory.
(based on bosonic string Mandelstam; Cremmer, Gervais)
(ii) With Brink. Type IIB light-cone gauge string field theory.
(iii) Formulation of type II supergravities in light-cone gauge (anticipated by Nahm's classification but missed).

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

We decided to resume work together the following year.

1983. Autumn at Queen Mary, London

(i) Searched for a covariant formulation of superstring action after intense confusion. Rediscovered κ-symmetry (Siegel's point superparticle).

Need to interpret physical SO(8) spinors S^a as half a covariant chiral (16-component) ten-dimensional spinors, Θ

$$S_1 \sim \Gamma^+ \Theta_1 \,, \qquad S_2 \sim \Gamma^+ \Theta_2$$

Requires a large fermionic local symmetry

Eventually "guessed" covariant action with local fermionic symmetry

$$S = \frac{1}{\pi} \int d\sigma \, d\tau (L_1 + L_2)$$

where

$$L_1 = -\frac{1}{2} \sqrt{-g} g^{\alpha\beta} \, \Pi^{\mu}_{\alpha} \, \Pi_{\beta \, \mu} \qquad \Pi^{\mu}_{\alpha} = \partial_\alpha X^\mu - i \bar{\Theta}_r \, \Gamma_\mu \, \Theta_r$$

and

$$\begin{aligned} L_2 \quad = \quad & -i\epsilon^{\alpha\beta} \, \big(\partial_\alpha X^\mu [\bar{\Theta}_1 \Gamma_\mu \partial_\beta \Theta_1 - \bar{\Theta}^2 \Gamma_\mu \partial_\beta \Theta^2] \\ & -i \bar{\Theta}^1 \Gamma_\mu \partial_\alpha \Theta^1 \; \bar{\Theta}^2 \Gamma_\mu \partial_\beta \Theta^2 \big) \end{aligned}$$

Wess-Zumino term

Looks like a horrible interacting world-sheet theory, BUT it possesses remarkable symmetries.

Obviously world-sheet reparamterization invariant.

Possesses global N=2 space-time SUSY: $\Theta_r \to \Theta_r + \epsilon_r$

Local fermionic κ symmetry:

$$\delta_\kappa \Theta_r = 2i \Pi^\mu_\alpha \, \Gamma_\mu \, \kappa^r_\beta$$

$$\delta_\kappa X^\mu = i \bar{\Theta}_r \, \Gamma^\mu \, \delta_\kappa \Theta_r$$

$$\delta_\kappa g_{\alpha\beta} = \dots$$

Where κ^r_β is a *self-dual vector* fermionic parameter. Note that Θ_r are world-sheet *scalars*. But upon fixing the light-cone gauge they become world-sheet *spinors* S_r.

(ii) Incorporates space-time supersymmetry, RR fluxes, … BUT quantization is very (very!) subtle – no kinetic term for Θ .

(iii) Developed a uniform formalism for open and closed light-cone gauge superstring field theory that allowed explicit calculations of amplitudes.

Also:

UK summer workshop in Brighton. With Brink and others. Wilczek emphasized Type I chiral gauge and gravitational anomaly issue (as had Witten).

First (??) string conference in Queen Mary (£120 budget)

Gravitational anomalies - absence of anomalies in type IIB Supergravity, Alvarez-Gaume and Witten (why did Witten not write String paper until 1984?).

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

(iii) Developed a uniform formalism for open and closed light-cone gauge superstring field theory that allowed explicit calculations of amplitudes.

Also:

UK summer workshop in Brighton. With Brink and others. Wilczek emphasized Type I chiral gauge and gravitational anomaly issue (as had Witten).

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We decided to resume work together the following year.

1984. Summer in Aspen.

Set about Type I string theory anomaly calculation.

Many experts present:
Bardeen, Zumino, Zee; Method of descent for non-abelian gauge and gravitational anomalies
Friedan, Shenker; BRST ghosts for strings; beta function

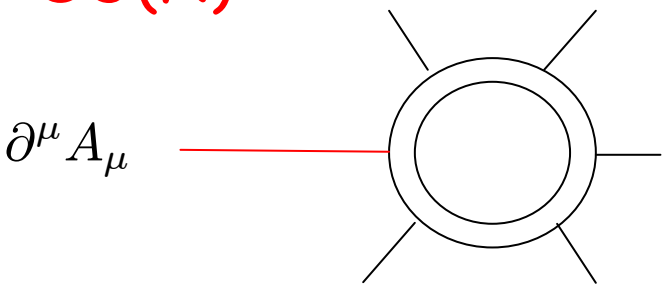
Many others at higher-dimensional supergravity program

We could not use Pauli-Villars, but I had rough notes (by Osborn) on a standard momentum cut-off procedure For calculating the triangle anomaly.

In ten dimensions chiral gauge anomalies arise from hexagon diagrams with external gauge bosons.

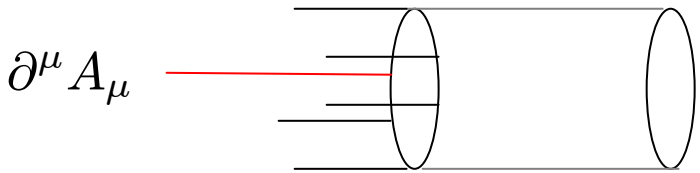
Anomalous hexagon diagrams: Five gluons coupling to divergence of axial current

SO(N)

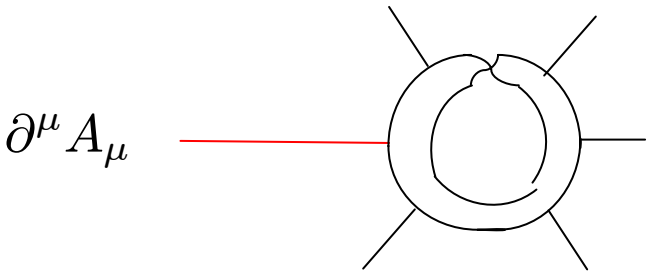


Annulus

N

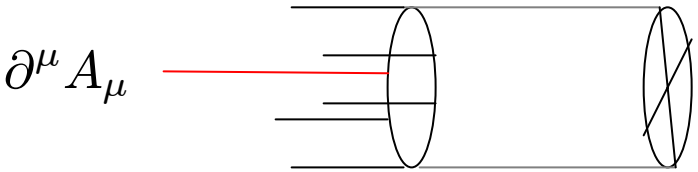


Cylinder

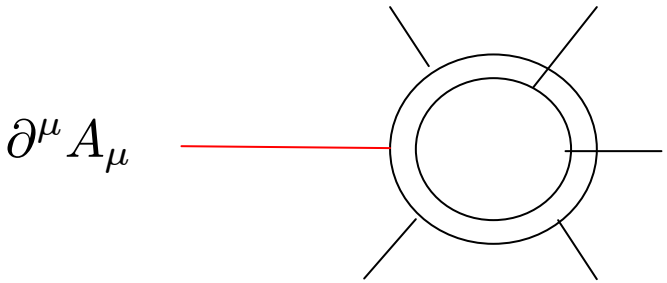


Mobius strip

-32

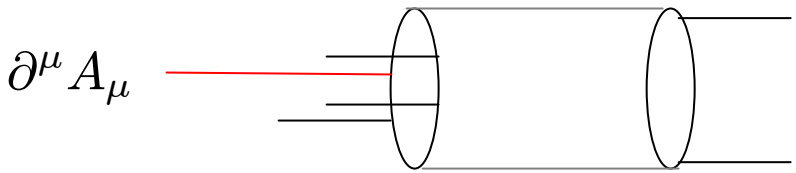


Cross-cap



Nonplanar annulus

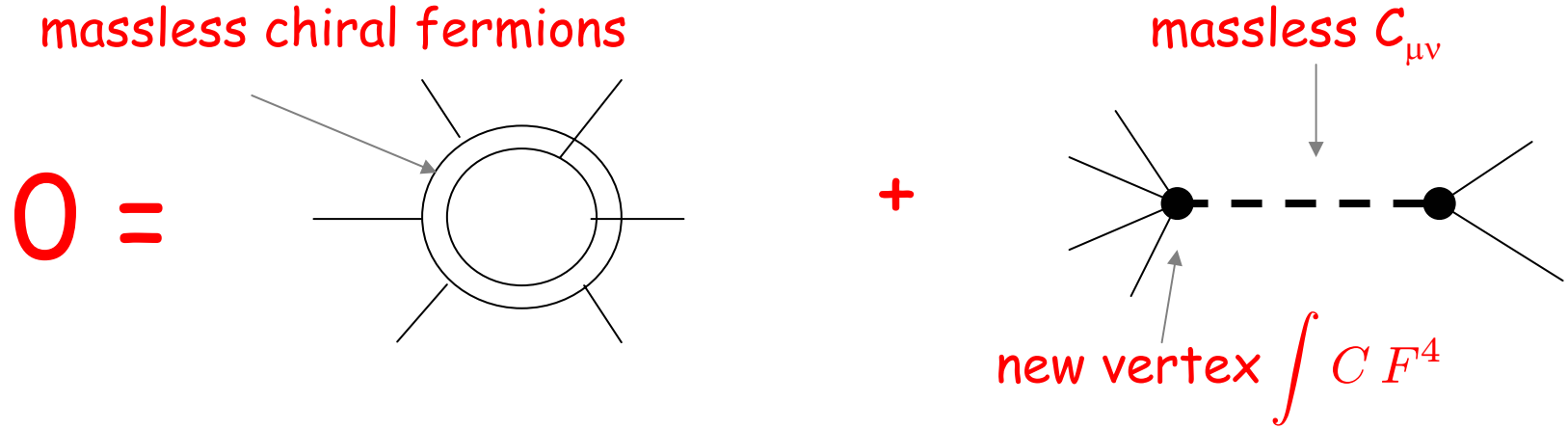
0



Nonplanar cylinder

(i) Total gauge anomaly vanishes for SO(32).

Since anomalies are infrared effects they should be Understandable in the low energy field theory limit.
In this limit the vanishing of the nonplanar annulus/cylinder is due to a cancellation between the one-loop nonplanar 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.



No independent 6th order Casimir of SO(32) in vector rep.

Also gravitational anomalies cancel with matter fields in dimension 496 = 16 X 31 representation.

Note that $E_8 X E_8$ has same dimension, but there was no string description. However, low energy cancellation again follows from absence of independent 6th order Casimir and dimension of group = 496 (revised version of paper).

Larry Yaffe communicated content of my seminar at Aspen to Princeton and Witten wrote his first string paper very quickly (~ c) - well before we had written our paper.

(ii) The SO(32) open string is also finite at one loop, when suitably regulated (as was type II).

1984. Sep-Dec in Caltech.

(i) Completed hexagon loop calculation.

"STUFF HAPPENED"

(ii) With West we came "close" to formulating an $E_8 X E_8$ bosonic string – BUT lacked the bizarre insight that gave the Heterotic String by Gross, Harvey, Martinec, Rohm
c.f. Santa Fe meeting (nov. 1984).

(ii) With West 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 used by Candelas, Horowitz, Strominger, Witten
(received by **ZAP-MAIL** at the Gainsville Christmas party!)

1985

The world had changed –

Furthermore, John met Patricia – no longer batchelors

late-1985 - mid-1986

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

Postscript:

1980's-90's work on superstring Dirichlet boundary conditions; T-duality between Neumann and Dirichlet conditions; preserve $\frac{1}{2}$ 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 more.

MANY SURPRISES YET TO COME