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1. ?

2. Renormalization

3. Quark Confinement
and magnetic monopoles

4. String Theory ...

5. What next ?

1. Renormalization

$\lesssim$ 1970: Quantum Field Theory "did not work"

Except: Qu. Electro Dynamics (QED)

But: • neither streng nor weak interactions seemed to be QFT's

• QFT's, even if you manage to "renormalize", develop UV ghosts: the Landau ghost (thought to be inevitable)

• Renormalization was ugly anyway.

Yang-Mills theory: 1954

Higgs-Englert-Brout 1964

But: Goldstone theorem 1961

What is "spontaneous symmetry breakdown" ?

... why this ugly scalar ?

Difficulty with PERTURBATIVE RENORMALIZATION of massive vector theories :

Unitarity dictates Proca propagator

$$\frac{\delta_{\mu\nu} + \frac{k_\mu k_\nu}{M^2}}{k^2 + M^2 - i\varepsilon}$$

← divergent !

Now, $\frac{k_\mu k_\nu}{k^2 + M^2 - i\varepsilon}$ is the propagator of a SCALAR with derivative couplings

CAN YOU CANCEL THAT OUT ?

NO !! unitarity : scalar has $+\frac{k_\mu k_\nu}{M^2(k^2 + M^2 - i\varepsilon)}$

Now we know: look at large k :

3 vectors + 1 scalar = 4 particles

But, pure photons $\frac{\delta_{\mu\nu} - k_\mu k_\nu / k^2}{k^2 - i\varepsilon}$

have only 2 helicities

You want a HIGGS which decouples ...

Feynman 1963 
DeWitt 1967
Faddeev - Popov 1967

Ghosts! 

Veltman used this ghost to do the 1-loop diagrams for pure massive vector fields (without Higgs)

ONLY WORKS FOR 1 LOOP

2 insights needed:

1) that Higgs - Englert - Brout - modified Yang - Mills had the RIGHT ultraviolet structure for renormalization

- and that "SPONTANEOUS SYMMETRY BREAKING" keeps renormalizability intact, whereas "SOFT" symmetry breaking, by mass terms $\frac{1}{2}M^2 A_\mu^2$ SPOILS it !!

- and how to do it! HOW do the Faddeev - Popov ghosts restore unitarity & renormalizability ?

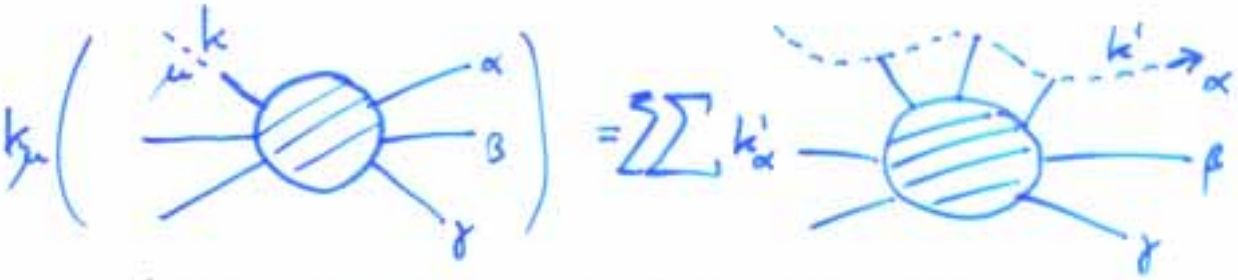
2) that β can be negative

G.'t H 1971, 1972

Essential ingredients for (perturbative) renormalization of gauge-theories: GENERALIZED WARD IDENTITIES

Veltman: you get such an identity if you perform a (source-dependent) gauge transformation.

I needed, to prove unitarity,



which was much harder: a FIELD-dependent gauge trf !

from this: gauge-invariance of theory with Faddeev-Popov ghost

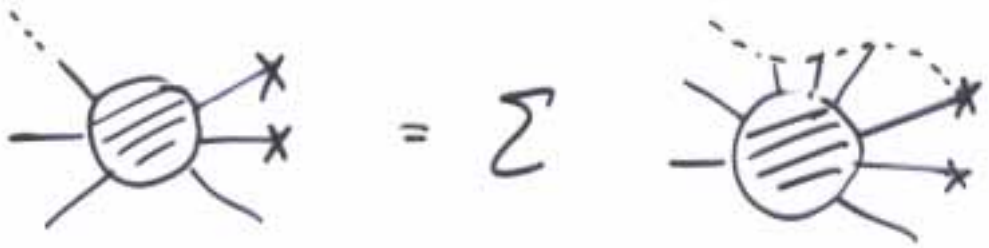
↳ unitarity, renormalizability

1971

identities only needed for S matrix: on shell

1971

J. C. Taylor: also off-shell:



1972

A.A. Slavnov: if you assume the entire theory to be gauge independent, you get this equation the easy way.

↳ Slavnov - Taylor identities

↓

An ESSENTIAL ingredient in the modern streamlined procedure called BRST quantization:

Becchi - Rouet - Stora - Tyupkin 1974

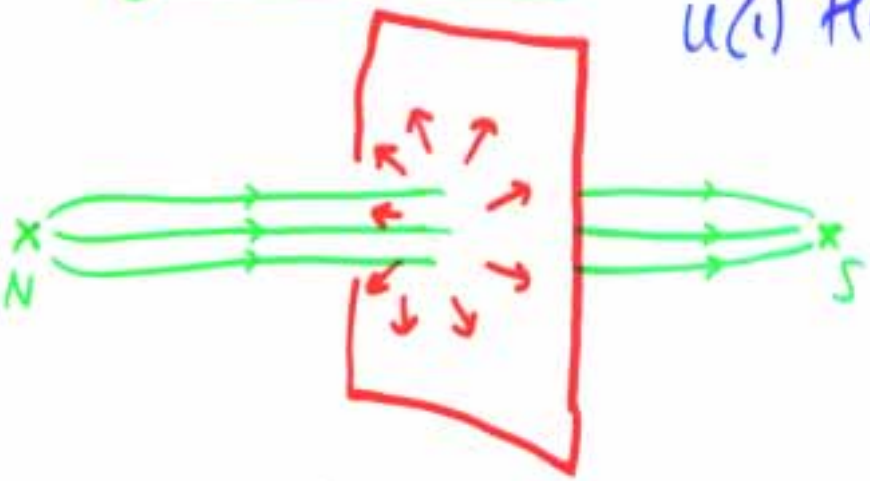
Quarks Confinement

1972: it had to be something "fundamental"

Zumino, Nielsen, Olesen 1973

The magnetic vortex

U(1) Higgs theory



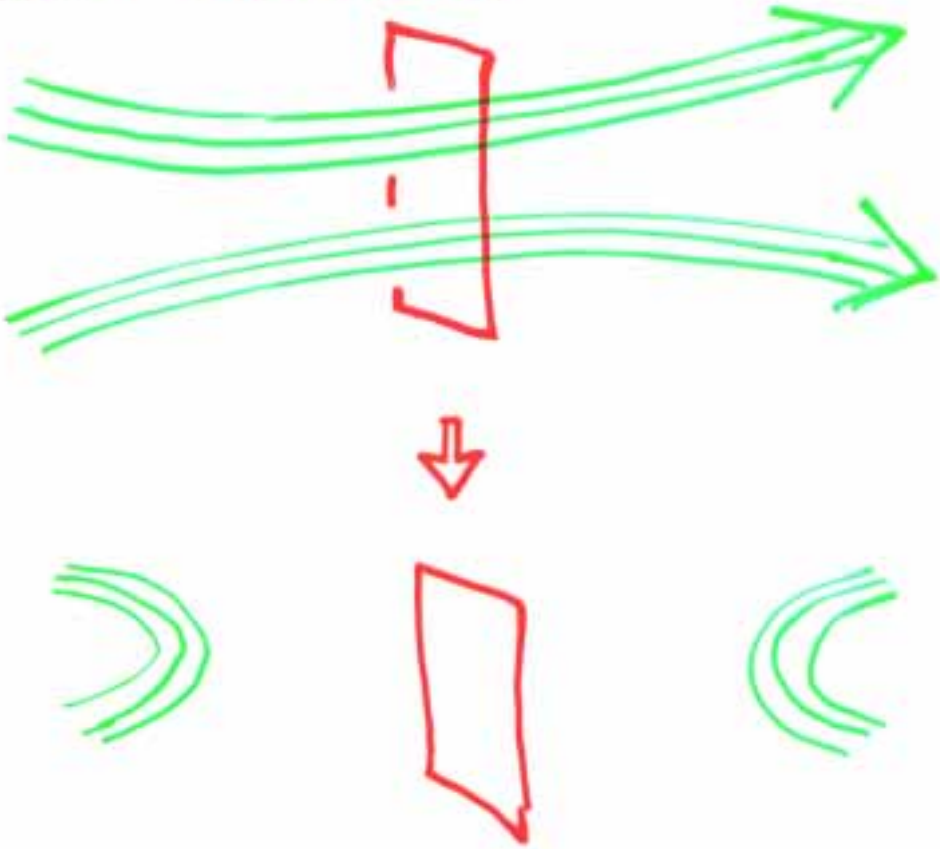
locally stable flux tube carrying 1 unit of magnetic flux

It occurs just like that in a SUPERCONDUCTOR

Question: what about an SU(2) Higgs theory ?

If $SU(2) \xrightarrow[\text{Higgs}]{} I$

then the vortex is NOT stable under addition:



But, how can that happen, if

$SU(2) \xrightarrow[\text{Higgs}]{} U(1) \xrightarrow[\text{superc}]{} I$

This gauge theory MUST generate magnetic monopoles ($g = 4\pi/e$)

1974

In some sense, the Higgs field was not essential for the existence of these monopole

Take now: a PURE (SU(2) or SU(3))
GAUGE THEORY

It will have "color electrically charged gluons" but also "color-magnetic monopol
the long-ranged "color electromagnetic interaction" between these is self-dual:

electric ↔ magnetic

Suppose that the color magnetic monopoles undergo HIGGS mechanism --

then you have color-ELECTRIC "Nielsen-Olesen" vortices ...

PRECISELY what you need to PERMANENTLY confine QUARKS

the vacuum is a color-magnetic superconductor.

Can this be phrased better ?

Non-Abelian gauge fixing:
without propagating ghosts
(or only very heavy ones ...)

Two steps:

1) $SU(N) \longrightarrow U(1)^{N-1}$

this can be done locally, directly:

take for instance G_{12}:

Diagonalize it: $G_{12} = \begin{pmatrix} \lambda_1 & & 0 \\ & \ddots & \\ 0 & & \lambda_N \end{pmatrix}$

this leaves only those Ω with

$[\Omega, G_{12}] = 0$: $\Omega \in U(1)^{N-1}$

2) Fix the gauge for $U(1)^{N-1}$ anyway you like; this is ordinary QED.

ordinary ?

In those points where $\lambda_1 = \lambda_2$, the residual gauge group is larger: $SU(2) \times U(1)^{N-2}$

↓ monopole singularities !

this theory $\equiv$ QED + monopoles !

Exact dual transformation now possible. These monopoles may be realized in the Higgs mode

We then have the "confinement phase"

... it still must be <u>proved</u> that this happens in QCD ...

" $SU(2)_{SM}$ is CONFINING " !!!

$SU(2)$ - QUARKS Q_i :

$$\psi = \begin{pmatrix} \nu \\ e \end{pmatrix} \qquad H = \begin{pmatrix} F + H_0 \\ 0 \end{pmatrix}$$

$SU(2)$ - MESONS :

$$\begin{cases} \bar{Q} Q & \to \nu, H_0 \\ \bar{Q} D_\mu Q & \to Z^0 \end{cases}$$

$SU(2)$ - BARYONS :

$$\begin{cases} \varepsilon^{ij} Q_i Q_j & \to e \\ \varepsilon^{ij} Q_i D_\mu Q_j & \to W^- \end{cases}$$

$SU(2)$ - ANTIBARYONS :

$$\varepsilon_{ij} \bar{Q}^i \bar{Q}^j \to e^+$$

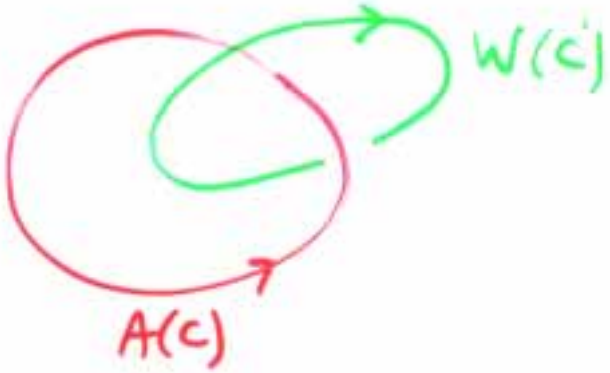
$$\varepsilon_{ij} \bar{Q}^i D_\mu \bar{Q}^j \to W^+$$

Loop operators :

Wilson loop : $W(C) \equiv \mathrm{Tr}\, \exp i \int_C A(x)\, dx$

Disorder loop: $A(C)$

= operator for a singular gauge trf



winding # of 2 loops

$$A(C)\, W(C') = W(C')\, A(C) \exp \frac{2\pi i}{N} n$$

If $\langle W(C) \rangle \to \exp(-\mu \cdot \text{length}(C))$ then

$\langle A(C) \rangle \to \exp - e \cdot \text{area}(C)$

(Higgs)

If $\langle A(C) \rangle \to \exp(-\mu \cdot \text{length}(C))$ then

$\langle W(C) \rangle \to \exp - e \cdot \text{area}(C)$

(confinement

$\langle A(C) \rangle$ and $\langle W(C) \rangle \to \exp(\text{shape}(C))$:

Coulomb

String Theory

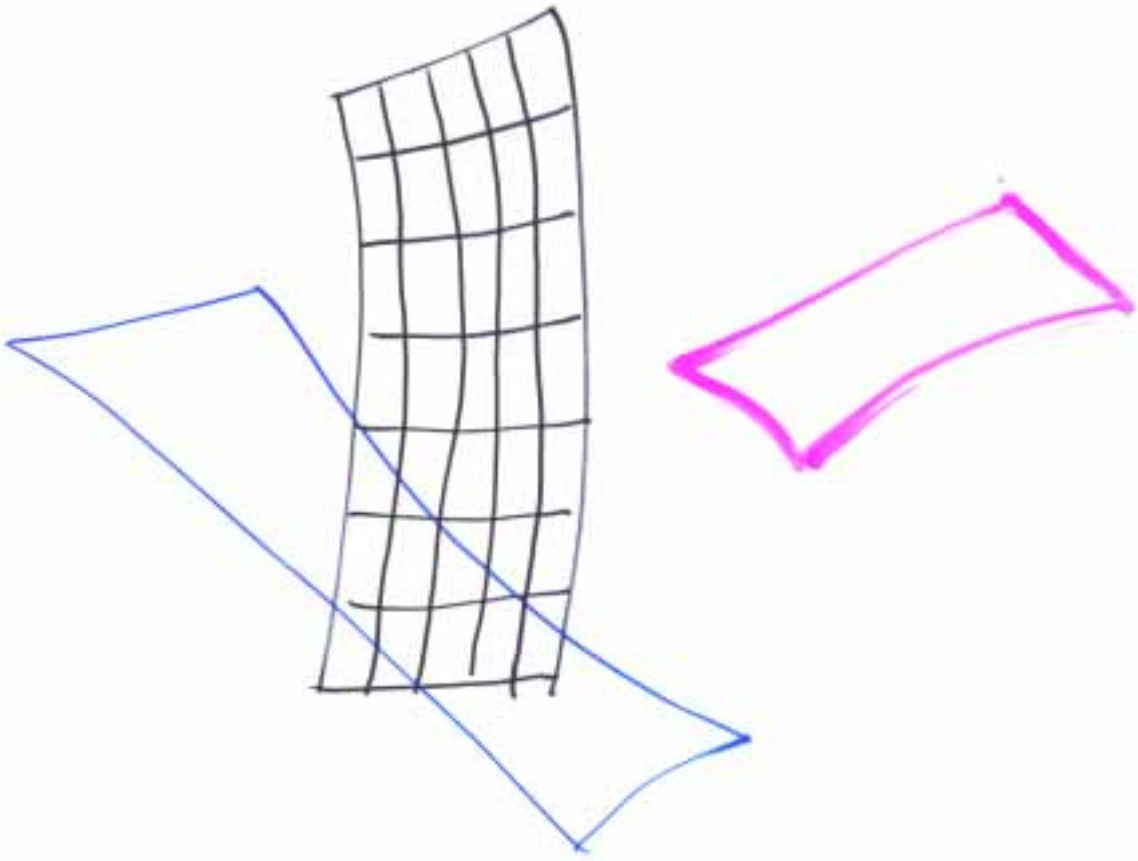
- BRST in string theory
- the zero-slope limit as a renormalizable YM + gravity
- Large N in string theory

- (Electric-Magnetic) duality in string theory

- Black Holes in string theory

AdS - CFT correspondence:

Holography in string theory



What about LOCALITY / CAUSALITY ?

Can ~~SUPER string theory~~ ~~brane theory~~ ~~M theory~~ ...

be reconciled with COMMON SENSE ?

WILL WE GET A **T.O.E.**

in ~~10 years~~ ~~20 years~~ ~~100 years~~ time ?

What will Quantum Mechanics look like, in a T.O.E. ?

Deterministic Quantum Mechanics:

select a special set of

COMMUTING

operators

↳ "classical physics"

Problem: $\frac{d\psi}{dt} = -iH\psi$ OK

$\langle H \rangle \geq 0$???

Dissipative Deterministic QM :

Once we restrict ourselves to commuting operators (at the Planck scale), we can allow for INFORMATION LOSS

– if we want to construct (3+1 dim) LOCAL laws –

What we presently call a "QUANTUM STATE" is only determined if you collect all information that DID NOT get lost

→ this is a NON-LOCAL definition

Quantum Mechanics may possibly be obtained from

CLASSICAL SYSTEMS

with

ATTRACTORS