

**Field Theory and Mathematics Panel**  
at the **THE FUTURE OF PHYSICS** Conference  
**Saturday, October 9, 2004**  
**Kavli Institute for Theoretical Physics**

*Moderator: Joseph Polchinski*

*Panelists: Hirosi Ooguri, Alexander Polyakov, Misha Shifman, Isadore Singer,  
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M. Shifman:

Unlike some models whose relevance to Nature is still a big “?”, Quantum Chromodynamics will stay with us forever.

QCD is a very rich theory supposed to describe the widest range of strong interaction phenomena: from nuclear physics to Regge behavior at large  $E$ , from color confinement to quark-gluon matter at high densities/temperatures (neutron stars); the vastest horizons of the hadronic world: chiral dynamics, glueballs, exotics, light and heavy quarkonia and mixtures thereof, exclusive and inclusive phenomena, interplay between strong forces and weak interactions, ... . The coupling constant can be strong or “medium” strong.

That is why I do not expect the *full* analytic solution to QCD to be found.

I am not a prophet, though, and have no direct line to God.<sup>1</sup> Therefore, in trying to make a prediction for the next 25 years, let me ask which breakthrough advances of nonperturbative QCD of today could have been foreseen 25 years ago.

**By the year 1980:**

- the OPE-based methods were on the rise;
- some crucial low-energy theorems shedding light on the QCD vacuum structure established;
- dual Meissner effect for color confinement conjectured;
- $1/N$  expansion as a useful classification tool suggested;
- SUSY gauge theories constructed and studied (almost exclusively, in the perturbative sector);
- instantons/monopoles discovered;
- hypothesis of the monopole-particle duality in  $\mathcal{N} = 4$  put forward.

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<sup>1</sup>Speaking of prophets, let me mention Joseph Glanvill’s book *Vanity of Dogmatizing*, published in London in 1661. In this book Joseph Glanvill, one of the founding members of Britain’s Royal Society, writes: “To them that come after us it may be as ordinary to buy a pair of wings to fly into remotest Regions; as now a pair of Boots to ride a Journey. [...] The restauration of grey hairs to Juvenility, and renewing the exhausted marrow, may at length be effected without a miracle. And the turning of the now comparatively desert world into a Paradise, may not improbably be expected from late Agriculture.” (The quotation courtesy of Lev Okun). The last prophecy, though, is still not quite *fait accompli* — for social rather than agricultural reasons.

This is all. Hints were there, but who could have guessed?

**Now:**

- OPE-based methods culminated in the 1990's;
- $1/N$  expansion became semi-quantitative in some problems;
- Triumph of SUSY-based methods for *QCD cousins* is unquestionable (A significant tool kit developed; the dual Meissner effect in  $\mathcal{N} = 2^*$  proven! Dualities in  $\mathcal{N} = 1$  discovered!);
- String and QCD practitioners are finally talking to each other, to their mutual benefit. Strings  $\leftrightarrow$  QCD. E.g. SYM “D-branes” ... .

**Predictions:**

(indirectly depend on external factors, such as SUSY discovery at LHC,...)

- \* SUSY-based methods will proliferate, allowing one to treat *closer* relatives of QCD, as well as important aspects of QCD *per se*;
- \*\* These methods will spread to some other strongly-coupled theories, e.g. those relevant to condensed matter physics;
- \*\*\* The gap between string theories and *realistic* strong-coupling gauge theories will continue to narrow, with two-way exchange of ideas;
- \*\*\*\* Combination of SUSY-based methods and  $1/N$  expansion will grow into a powerful *quantitative* tool.

*In summary, I expect a “hydrogen atom” of nonperturbative QCD to be found along these lines.*

Unlike models whose relevance to nature is ? QCD will  
stay with us

QCD is extremely rich:

- ★ Nuclear Physics

  - ★ Regge behavior

    - ★ QGM: high-T/high  $\mu$  (neutron stars)

      - ★ Richness of the hadronic world:

- ★ chiral;

- ★ light & heavy quarkonia;

- ★ glueballs & exotics;

- ★ exclusive & inclusive phenomena;

- ★ interplay between strong forces & weak interactions...

That's why I do not expect **FULL** analytic solution to QCD  
to be found

To normalize my predictions for next 25 years let me ask:  
“advances of nonpert. QCD foreseen 25 years ago?”

By the year 1980:

- ★ OPE-based methods on the rise (peaked in 90's);
- ★ Low-energy theorems (a few extra added in 90's);
- ★ Dual Meissner effect for confinement conjectured;
- ★  $1/N$  expansion  $\longrightarrow$  useful classification tool;
- ★ SUSY gauge field theories (pert);
- ★ Instantons & monopoles discovered
- ★ Monopole-particle duality in  $\mathcal{N}=4$  conjectured

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Now:

- ✳  $1/N$  became semi-quantitative;
- ✳ Triumph of SUSY-based methods for QCD cousins (e.g.  $\mathcal{N}=2$ );
- ✳ Strings  $\leftrightarrow$  QCD, e.g. SYM “D-branes”;
- ✳ Dualities in gauge theories, sigma models ...

Predictions (indirectly depend on external factors, e.g. LHC):

SUSY-based methods  
will proliferate

Closer relatives of QCD

Aspects of QCD per se

Gap between strings and  
"realistic" gauge theories  
will narrow from both sides

Other str-coupl.  
theories/cond.matter

Combination of SUSY and  $1/N$  (or  $g_{st}$ )  
will become a quantitative tool

A "hydrogen atom" of nonperturbative QCD  
will be found along these lines