Origin of Color

O. W. Greenberg
University of Maryland

Frascati

April 14, 2016

John Templeton Foundation

UNIVERSITY OF MARYLAND

Outline

- Usefulness of useless knowledge
- Stretching the types of statistics
- Resolution of statistics paradox

The Usefulness of Useless Knowledge, Flexner 1939

- "… the pursuit of these useless satisfactions proves unexpectedly the source from which undreamed-of utility is derived."

The Usefulness of Useless Knowledge

- Faraday and Prime Minister
- Rutherford and nuclear physics

- Planck was warned in 1878, structure of theoretical physics had been completed
- String theory will be the theory of everything

Istanbul

- NATO summer school at Robert College in Bebek, 1962
  - organized by Feza Gürsey
- Sidney Coleman, Shelly Glashow, Louis Michel, Giulio Racah, Eugene Wigner

Curiosity driven research

- Bosons and fermions were well known.
- H.S. Green had introduced "parastatistics."
- My motivation was to "stretch" the formalism of quantum field theory.

- I first introduced the word parastatistics 1963 in a paper with Gian-Fausto DellAntlonio and George Sudarshan. We submitted our paper to Physics Letters where it was promptly accepted. I gave a talk on this joint work at Saclay that summer (1963).

- Albert (Bacco) Messiah pointed out an error in the paper and I was able to stop publication.

- This started a collaboration with Messiah that resulted in two long papers.

- One on quantum mechanics of particles that transform as representations other than the one-dimensional representations of the symmetric group (which correspond to Bose or Fermi statistics).

- We concluded that quantum mechanics allowed particle statistics other than Bose or Fermi; however all known particles obeyed either Bose or Fermi statistics.

- The other on field theories of particles that obey statistics other than Bose or Fermi.
- Our conclusion at that time was that all known particles are either bosons or fermions.
- The motivation was to “stretch” the formalisms of quantum mechanics and quantum field theory. I had no application in mind.

Work of H.S. Green

- We developed Green's ideas, parastatistics come in two families, each labeled by an integer, p=1, 2, 3…

Parastatistics

- H.S. Green’s parastatistics (1953) as a generalization of each type.
- Boson—paraboson, order p,
- Fermion—parafermion, order p;
- p=1 is Bose or Fermi.

Primer on parastatistics

$$q = \sum_{\alpha=1}^{p} q^{(\alpha)},$$

$$[q^{(\alpha)}(x), q^{(\alpha)\ \dagger}(y)]_{+} = \delta(\mathbf{x} - \mathbf{y}), x^0 = y^0$$

$$[q^{(\alpha)}(x), q^{(\beta)\ \dagger}(y)]_{-} = 0, x^0 = y^0, \alpha \neq \beta$$

Discovery of hidden color charge for quarks

Background to discovery

(personal reminiscences)

Disparate influences

- Very simple ideas used to classify newly discovered particles.

- Sophisticated mathematical techniques based on quantum field theory.

Wightman, Axiomatic Quantum Field Theory

- My PhD thesis: Asymptotic condition in quantum field theory
  - Formalization of LSZ scattering theory.
  - Purely theoretical—no numbers, except to label pages & equations.
- Operator-valued distributions, relative mathematical rigor.

Interest in identical particles

- Why only bosons or fermions?

- Are there other possibilities?

Generalized statistics

- First quantized theory allows all representations of symmetric group.

  A.M.L. Messiah and O.W. Greenberg, Phys. Rev. 136, B248, (1964)

- Theorems show generality of parastatistics
  – Green's ansatz not necessary.

  O.W. Greenberg and A.M.L. Messiah, Phys. Rev.138, B1155 (1965)

1964

- Crucial year for discovery of quarks and color.

The crucial year, 1964

- Zweig—"aces"—constituent quarks.
  G. Zweig, 1964, CERN articles.
- Gell-Mann—"quarks"—current quarks.
- M. Gell-Mann, 1964, Phys. Lett. 8, 214.

- Why only qqq & q-qbar?
  - No reason in original models.

Background to paradox, 1964

- **Relativistic SU(6), Gürsey & Radicati**
  F. Gürsey and L.A. Radicati, 1964, Phys. Rev. Lett. 13, 173.

- **Generalize Wigner's nonrelativistic nuclear physics idea**
  - **to combined $SU(2)_I$ with $SU(2)_S$ to get an SU(4) to classify nuclear states.**

- **Gürsey & Radicati combined $SU(3)_f$ with $SU(2)_S$ to get an SU(6) to classify particle states.**

SU(6) classifications

$$q \sim (u, d, s), \text{ in } SU(3)_f$$

$$(1/2) \sim (\uparrow, \downarrow)$$

$$\mathbf{6} = (q, 1/2) \sim (u_\uparrow, u_\downarrow, d_\uparrow, d_\downarrow, s_\uparrow, s_\downarrow) \text{ in } SU(6)_{fS}$$

$$SU(6)_{fS} \to SU(3)_f \times SU(2)_S = (u, d, s,) \times (\uparrow, \downarrow)$$

Mesons

$$\mathbf{6} \otimes \mathbf{6}^{\star} = \mathbf{1} + \mathbf{35}$$

$$\mathbf{35} \rightarrow (\mathbf{8}, \mathbf{0}) + (\mathbf{1} + \mathbf{8}, \mathbf{1})$$

$$(K^{+}, K^{0}, \pi^{+}, \pi^{0}, \pi^{-}, \eta^{0}, \bar{K}^{0}, \bar{K}^{-})$$

$$(K^{\star\ +}, K^{\star\ 0}, \phi^{0}, \rho^{+}, \rho^{0}, \rho^{-}, \omega^{0}, \bar{K}^{\star\ 0} \bar{K}^{\star\ -})$$

- Statistics not relevant for mesons, q q-bar

- Statistics relevant for baryons
- qqq

Baryons

$$\mathbf{6} \otimes \mathbf{6} \otimes \mathbf{6} = \mathbf{56} + \mathbf{70} + \mathbf{70} + \mathbf{20}$$

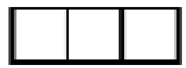
$$\mathbf{56} \rightarrow (\mathbf{8}, \mathbf{1/2}) + (\mathbf{10}, \mathbf{3/2})$$

$$(p^+, n^0, \Lambda^0, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-)$$

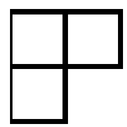
$$(\Delta^{++}, \Delta^+, \Delta^0, \Delta^-, Y_1^{\star\ +}, Y_1^{\star\ 0}, Y_1^{\star\ -}, \Xi^{\star\ 0}, \Xi^{\star\ -}, \Omega^-)$$

Statistics paradox

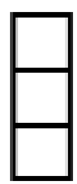
- 56



- 70



- 20



Magnetic moment ratio, 1964

- Beg, Lee, & Pais μ_p / μ_n

$$|p^+_\uparrow\rangle = \frac{1}{\sqrt{3}} u^\dagger_\uparrow (u^\dagger_\uparrow d^\dagger_\downarrow - u^\dagger_\downarrow d^\dagger_\uparrow)|0\rangle$$

$$|n^0_\uparrow\rangle = \frac{1}{\sqrt{3}} d^\dagger_\uparrow (u^\dagger_\uparrow d^\dagger_\downarrow - u^\dagger_\downarrow d^\dagger_\uparrow)|0\rangle$$

$$\mu_B = \langle B_\uparrow | \mu_3 | B_\uparrow \rangle$$

$$\mu_3 = 2\mu_0 \sum_q Q_q S_q, \quad Q_q = (\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})$$

$$\mu_p = 2\mu_0 \cdot \frac{1}{3}\{2[\frac{2}{3} \cdot 1 + (-\frac{1}{3}) \cdot (-\frac{1}{2})] + [(-\frac{1}{3}) \cdot \frac{1}{2}]\} = \mu_0$$

$$\mu_n = -\frac{2}{3}\mu_0 \qquad m_N/2.79 = 336MeV$$

Significance of magnetic moment calculation

- Simple one-line calculation gave ratio accurate to 3%.
- Very convincing additional argument for quark model.
- Quarks have concrete reality.

Spin-statistics theorem

- Particles that have integer spin must obey Bose statistics

- Particles that have odd-half-integer spin must obey Fermi statistics.

Generalized spin-statistics theorem

- Not part of general knowledge in 1964:
- Particles that have integer spin must obey parabose statistics:
- Particles that have odd-half-integer spin must obey parafermi statistics.
- Each family labeled by an integer p; p=1 is ordinary Bose or Fermi statistics.

Parafermi quark model, 1964

- Suggested model in which quarks carry order-3 parafermi statistics.

- Allows up to 3 quarks in same space-spin-flavor state without violating Pauli principle, so statistics paradox is resolved.

- **This was the introduction of hidden charge of quarks now called color**.
  O.W. Greenberg, 1964, Phys. Rev. Lett. 13, 598.

My response to quark model

- Exhilarated—resolving statistics problem seemed of lasting value.

- Not interested in higher relativistic groups;
  - from O'Raifeartaigh's & my own work I knew that combining internal & spacetime symmetries is difficult or impossible.

- To test this idea I worked out the excited states that would occur if the "symmetric" quark model were correct.

Baryon spectroscopy

- Hidden parafermi (color) degree of freedom takes care of required antisymmetry of Pauli principle.

- Quarks can be treated as bosons in visible space, spin & flavor degrees of freedom.

- Predictions of excited states of baryons

- Baryon spectroscopy

Table of excited baryons

- Developed simple bound state model with s & p state quarks in 56, L=0+ & 70, L=1- supermultiplets.

Table II. Low-lying states in paraquark model of baryons.[a]

Orbitals configuration	L	Parity	Young diagram	(SU(3), J) decomposition	Total multiplicity	Total no. of I multiplets
s^3 (pure)	0	+	(3)	$(\underline{8}, J=1/2)$ $(\underline{10}, J=3/2)$	56	8
s^2p^1 (spurious)	1	−	(3)	$(\underline{8}, J=1/2, 3/2)$ $(\underline{10}, J=1/2, 3/2, 5/2)$	168	20
s^2p^1 (pure)	1	−	(2, 1)	$(\underline{1}, J=1/2, 3/2)$ $(\underline{8}, J=1/2, 3/2, 5/2)$ $(\underline{10}, J=1/2, 3/2)$ $(\underline{8}, J=1/2, 3/2)$	210	30
s^1p^2, s^2d^1 (mixed)	2	+	(3)	$(\underline{8}, J=3/2, 5/2)$ $(\underline{10}, J=1/2, 3/2, 5/2, 7/2)$	280	24
s^1p^2, s^2d^1 (mixed)	2	+	(2, 1)	$(\underline{1}, J=3/2, 5/2)$ $(\underline{8}, J=1/2, 3/2, 5/2, 7/2)$ $(\underline{10}, J=3/2, 5/2)$ $(\underline{8}, J=3/2, 5/2)$	350	34
s^1p^2, s^2d^1 (mixed)	1	+	(2, 1)	$(\underline{1}, J=1/2, 3/2)$ $(\underline{8}, J=1/2, 3/2, 5/2)$ $(\underline{10}, J=1/2, 3/2)$ $(\underline{8}, J=1/2, 3/2)$	210	30
s^1p^2 (pure)	1	+	(1, 1, 1)	$(\underline{8}, J=1/2, 3/2)$ $(\underline{1}, J=1/2, 3/2, 5/2)$	60	11

The agreement of data on excited baryons confirmed the predictions of color for excited baryons, and resolved the paradox concerning the permutation symmetry of the quarks in the 56.

For 10 years baryon spectroscopy was the only test of the existence of color.

Later developments of baryon spectroscopy

- Greenberg & Resnikoff
- Dalitz & collaborators
- Isgur & Karl
- Riska & collaborators

Attempts to make higher dimensional relativistic theory

- Pais, Rev. Mod. Physics 38, 215 (1966).

- U(6,6)
- U(12)
- GL(12,C)

- Pais, Salam, et al, Freund, et al.

Unsuccessful solutions to statistics paradox

- Complicated antisymmetric ground state

- Quarks are not real anyway

- Other models, baryonettes, etc.

Disbelief in physics community

- Not generally accepted for 10 years
- J. Robert Oppenheimer
- Steven Weinberg

Gave Oppenheimer preprint in Princeton, 1964

- At conference at University of Maryland
- ***"Greenberg, it's beautiful!"***
  - I was very excited.

Oppenheimer's response, *(continued)*

"but I don't believe a word of it."

– I came down to earth.

My response to Oppenheimer's comment

- *Not discouraged.*

- *But did not ask why he did not believe it.*

Weinberg: The making of the standard model

- ***"At that time I did not have any faith in the existence of quarks."*** (1967)

Sources of skepticism about color (1964 - 1968)

- Quarks had just been suggested (1964).
- Fractional electric charges had never been seen (1964).
- Gell-Mann himself was ambiguous (1964).

Skepticism *(continued)*

- Assuming hidden charge on top of fractionally charged unseen quarks.

- Seemed to stretch credibility to the breaking point.

- Parastatistics was unfamiliar.

Gell-Mann's comments

- *"It is fun to speculate …if they were physical particles of finite mass (instead of purely mathematical entities as they would be in the limit of infinite mass)...A search … would help to reassure us of the non-existence of real quarks."* (1964)

Evidence for color

- 1964, O.W. Greenberg, baryon spectra

- 1969, S. Adler, J. Bell & R. Jackiw explained pi to 2 gamma decay rate.

- From 1964 to 1969 baryon spectroscopy was the only experimental evidence for color.

Saturation

- Why are hadrons made from just two combinations,

$$qqq \text{ and } q\bar{q}$$

Work with Zwanziger, 1966

- Surveyed existing models, constructed new models to account for saturation.

- Only models that worked were parafermi model, order 3, and equivalent 3-triplet or color SU(3) models.

Gauge theory of color

- Explicit color SU(3)—Han-Nambu, 1965.

- Used 3 dissimilar triplets in order to have integer charges-not correct.

- *"Introduce now eight gauge vector fields which behave as (1,8), namely as an octet in SU(3)".* **This was the introduction of the gauge theory of color.**

Nambu's paper in Weisskopf festschrift

- In Preludes in Theoretical Physics, (North Holland, 1966).

- Discussed mass formula based on octet gluon exchange.

- Very overlooked paper

Fractional vs. integer electric charges for quarks

- Fractional charges not seen—led to doubt
- Fractional charges allow exact color symmetry
- Integer charges for quarks conflict with exact color symmetry and with direct experimental evidence

No-go theorems

- Supersymmetry is only way to combine internal & spacetime symmetries in a larger group—

Greenberg, O'Raifeartaigh,

Coleman & Mandula,

Haag, Lopuszanski & Sohnius.

Equivalence as classification symmetry

States that are bosons or fermions in parafermi model, order 3,

are in

1-to-1 correspondence with states that are color singlets in SU(3) color model.

Color & electromagnetism commute

- Identical fractional electric charges allow color & electromagnetism to commute.
- Allows color to be an exact, unbroken, symmetry.
- Crucial part of understanding of quantum chromodynamics, QCD.

Two facets of strong interaction

1 Color as classification symmetry & global quantum number

- parafermi model (1964)
- was first introduction of color as global quantum number.

Two facets of strong interaction

2 SU(3) color as local gauge theory

- Han-Nambu model (1965) was first introduction of gauged SU(3) color.

General acceptance of color

3 General acceptance required a surprizingly long time in which many new ideas were assimilated.

Gradual diffusion of ideas

Greenberg, Zwanziger, 1966

parastatistics for bosons and fermions equivalent to color

Bjorken, scaling prediction, 1966, 1968

Feynman, parton model, 1969

Callan, Gross, spin of partons is ½, 1968

- The first rapporteur who preferred the parastatistics model was Harari at the Vienna conference in 1968.

Conflicting issues

- Quarks, fiction, mathematical, confined, or real?

- Quark charges, integral or fractional?

  Quark statistics, fermi, para, explicit color?

- Gluons, singlets or octets?

Main aspects of color

- **Color — hidden 3-valued degree of freedom for quarks.**

- **Colored quarks—fractional electric charges.**

- **Hidden degree of freedom is gauged.**

- **Hidden color gauge group commutes with electromagnetism.**

Color as charge
Color as gauge symmetry

- Color as charge - analogous to electric charge in electromagnetism.

- Color as gauge symmetry - analogous to U(1) symmetry of electromagnetism.

- Two independent discoveries.

Full understanding of color

- **Full understanding of color emerged from work of:**
  - **Greenberg, 1964**
  - **Han and Nambu, 1965**
- Neither got everything in final form at the beginning.

Full Acceptance of Color

- Not generally accepted for 10 years.
- Oppenheimer and Weinberg were representative of many in the physics community who were skeptical.
- Even Gell-Mann did not accept the reality of quarks and color, unlike Zweig.

The usefulness of useless knowledge

The discovery of color came from useless knowledge–

- playing around with types of statistics that don’t appear in nature,
- led to the discovery of a new, hidden charge, color,
- even if not believed by the physics community for 10 years.

The support from the *John Templeton Foundation* in the framework of the project:

58158: Hunt for the "impossible atoms": the quest for a tiny violation of the Pauli Exclusion Principle, ***Implications for physics, cosmology and philosophy***

is acknowledged