

THE METAMORPHOSES OF THE QUARK

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THE DEVELOPMENT OF THE QUARK IDEA
FROM THE INVENTION 50 YEARS AGO
TO THE QUARKS OF QCD

“ONLY THE CHARGE HAS NOT BEEN CHANGED”

A Celebration of Mike Creutz' Career
Brookhaven September, 2014

GOAL OF THIS TALK

- Trace the Development of the Quark Concept
- The Antecedents of each Development
 - Their Origins and Context
 - The Preparations for each Development
- How Relevant Ideas Changed with Context
- Notice how Progress at Each Step Used Ideas that were in (at least some) Theorists “Toolkit”
- [Speaker’s Apology]: In order to give the ideas themselves prominence, I will not emphasize who made each breakthrough.

A LEPIDOPTERAL METAPHOR

Embryo
(Egg)



Larva
(Caterpillar)



Pupa
(Chrysalis)



Imago
(Adult Butterfly)

New Quantum Numbers
The Eightfold Way / Unitary Symmetry
Mesons $\sim \mathfrak{8}$ Baryons $\sim \mathfrak{8} + \underline{10}$
Fundamental Representation Absent

The Quarks: Fractional Charge Triplets
Are They Real? (Constituents of Hadrons)
Are They Just a Mathematical Shorthand?
Relationship to Weak Currents?

Thinking About Real Quarks —
Spin/Statistics Problem \rightarrow Parafermions
Color (New SU(3)!) — More Shorthand?
Still No Dynamics; Confinement a Mystery

Asymptotic Freedom \rightarrow Quarks = Partons
Promotion of Color to the Essence of
Strong Dynamics; Gluons a Color $\mathfrak{8}$
QCD the Theory of Strong Interactions

THE (PROTO-) EMBRYONIC STAGE

- The Context —
 - Elementary Particle Physics ca. 1960
- Discovery of New Particles and Resonances
- Nature and Treatment Unclear; Many Puzzles
- Quest for a Full Theory
 - Dynamical Approaches (*e.g.* S-Matrix) did not Succeed
- Symmetry Approach (less ambitious)
 - Maybe one could find a true property of the final theory before finding the final theory
 - Isospin known since 1930's
 - Strangeness made sense of decays (late 1950's)
 - Searches for Higher Symmetry

DEVELOPMENT OF UNITARY SYMMETRY

“THE EIGHTFOLD WAY”

- Composite Models were in the air, *e.g.*,
 - Constituents p, n, λ (“little” proton, neutron, Λ)
 - Mesons as $\bar{p}n$ (π^-), $\bar{p}\lambda$ (K^-), etc.
- Pre-quark Models had some success
- Higher Symmetry recognizable in Models
 - isospin in above if $m_p = m_n$, SU(3) if $m_p = m_n = m_\lambda$
- Focus on symmetry apart from models
 - “Global Symmetry” $SU(2) \otimes SU(2)$
 - “The Eightfold Way” SU(3)

SU(3) IN PARTICLE PHYSICS

Isospin
1930s

Strangeness
1950s

New
Particles

These were the Inputs and Impetus for
SU(3) Unitary Symmetry
New “Language” — Learned with Effort
The Legacy of Unitary Symmetry was

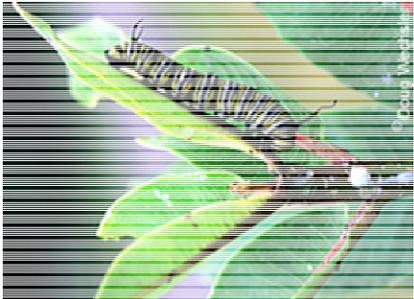
Symmetry Perceived
as a route to Progress

Familiarity with SU(3)
Tool for Future Use

SU(3) TECHNOLOGY LEARNED

- Symmetry “outgrew” composite models
- Representations for particles and interactions
 - Mesons in octets and singlets
 - Baryons in octets and decuplets (*n.b.* BNL)
- SU(3) breaking in an octet (mass formulae)
- Currents identified as elements of an octet
- MANY detailed successes
- BUT: Why only 8 and 10; what about 3, ...?

THE LARVA: THE QUARKS OF 1964



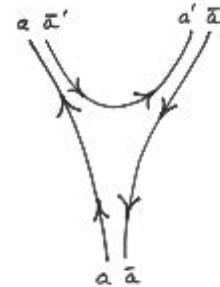
- Different from model constituents
- Defined by Fractional Charge
- Scandalous Idea - Widely scorned
- Triplet under Unitary Symmetry Group
 - (u, d) $J = \frac{1}{2}$ $I = \frac{1}{2}$ $S = 0$ $Q = (+\frac{2}{3}, -\frac{1}{3})$
 - s $J = \frac{1}{2}$ $I = 0$ $S = -1$ $Q = -\frac{1}{3}$
- Quarks Born with an Identity Crisis
 - Constituent Quarks, mass $\approx \frac{1}{3} M_{\text{proton}}$
 - Current Quarks, Pointlike objects, Massless?
 - Related by some unitary transformation?

LARVAL PARADOXES

Were Quarks actual physical objects, or just a mnemonic for tracking representations and symmetry breaking (*i.e.* $m_n \neq m_\lambda$)?

The case for Physical Quarks

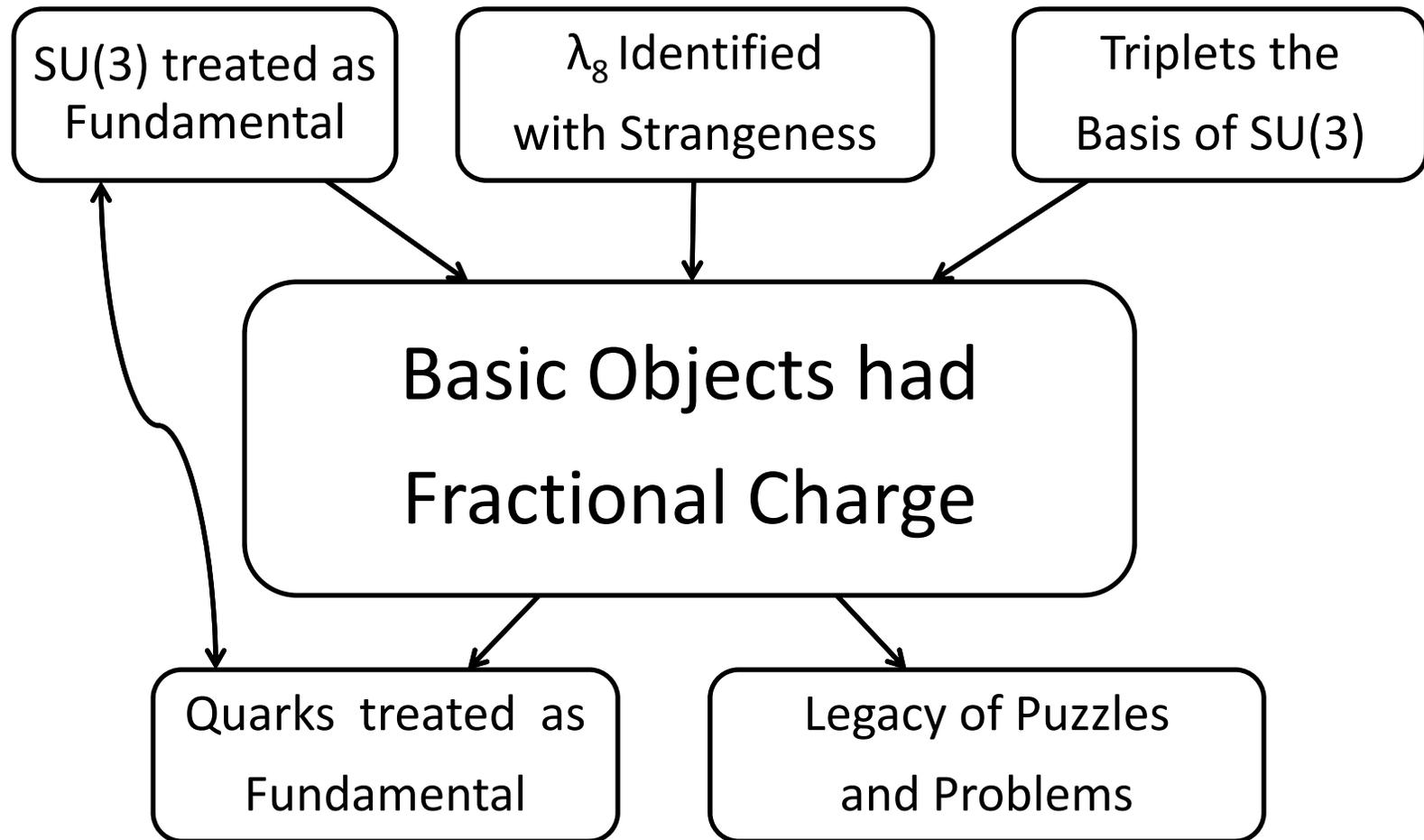
- Simple Non-Relativistic Picture
- Conservation of Quark Types
- Quark Model Quantitative Successes



The case against Physical Quarks

- Fractional Charge Never Observed
- No Natural Mechanism for Confinement
- No Direct Evidence, *e.g.* in scattering or decays

FRACTIONALLY CHARGED QUARKS

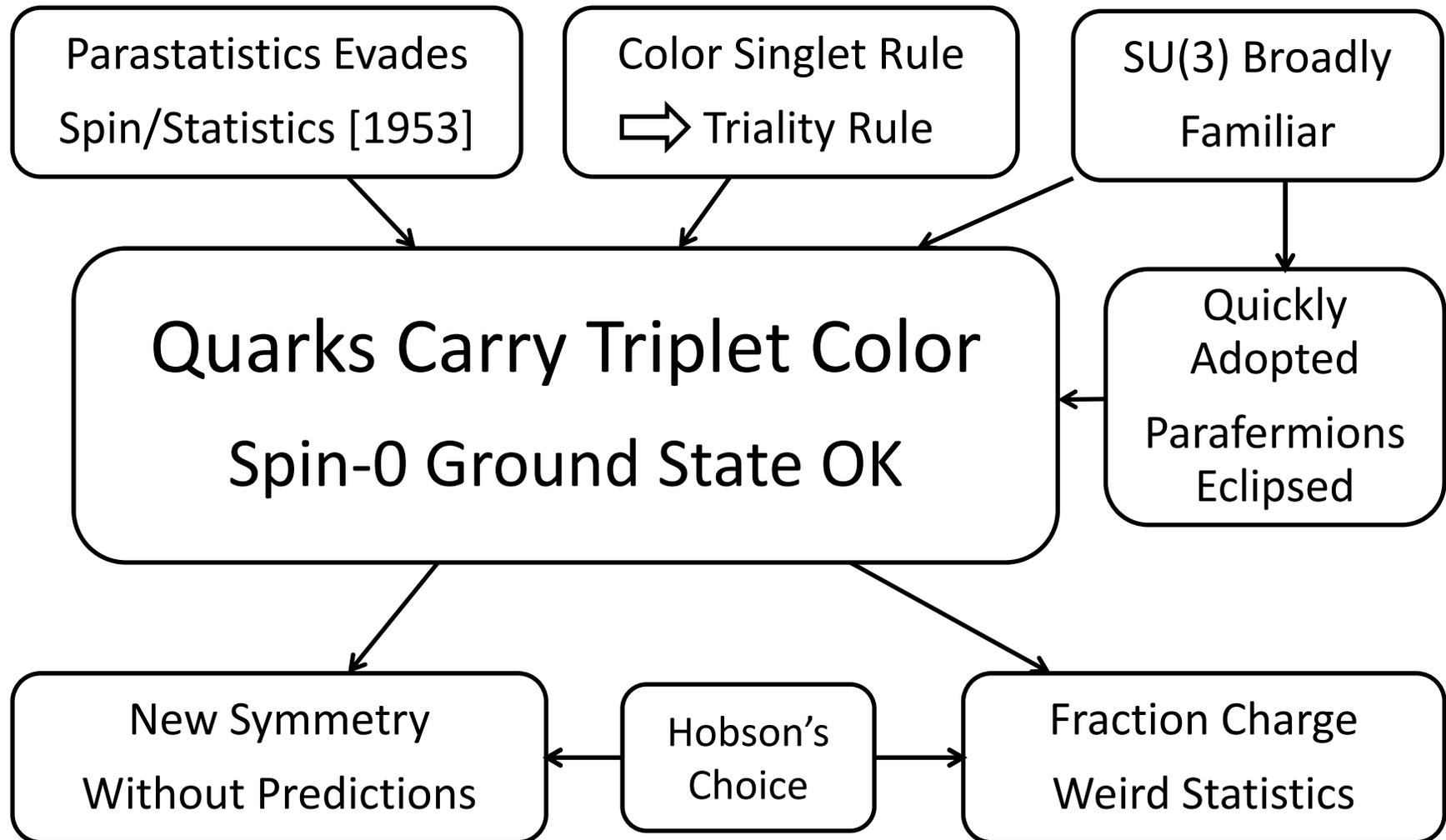


KEY PROBLEM — SPIN/STATISTICS

If quarks were real, and nucleons were bound states of 3 quarks, spin/statistics was a puzzle.

- Quarks (spin = $\frac{1}{2}$) should be fermions, but ground states are “always” s-wave, and hence symmetric in space
- Resolution was taking quarks or other triplets as order 3 parafermions [1953 — Theoretical Curio]
- Parafields were objects with exotic symmetry and selection rules (to evade spin/statistics theorem)
- Showed that Quarks not fatally flawed

COLOR AS A GLOBAL SYMMETRY



THE PUPA: REARRANGING THE PIECES



In the Chrysalis, all the larval structure dissolves and the living matter is (re)assembled into a spectacular butterfly

- In the 10 years since they were posited, quarks were as puzzling as ever.
- None of the essential questions about their nature had been unequivocally answered

WHILE QUARKS METAMORPHOSED ...

GREAT PROGRESS ELSEWHERE

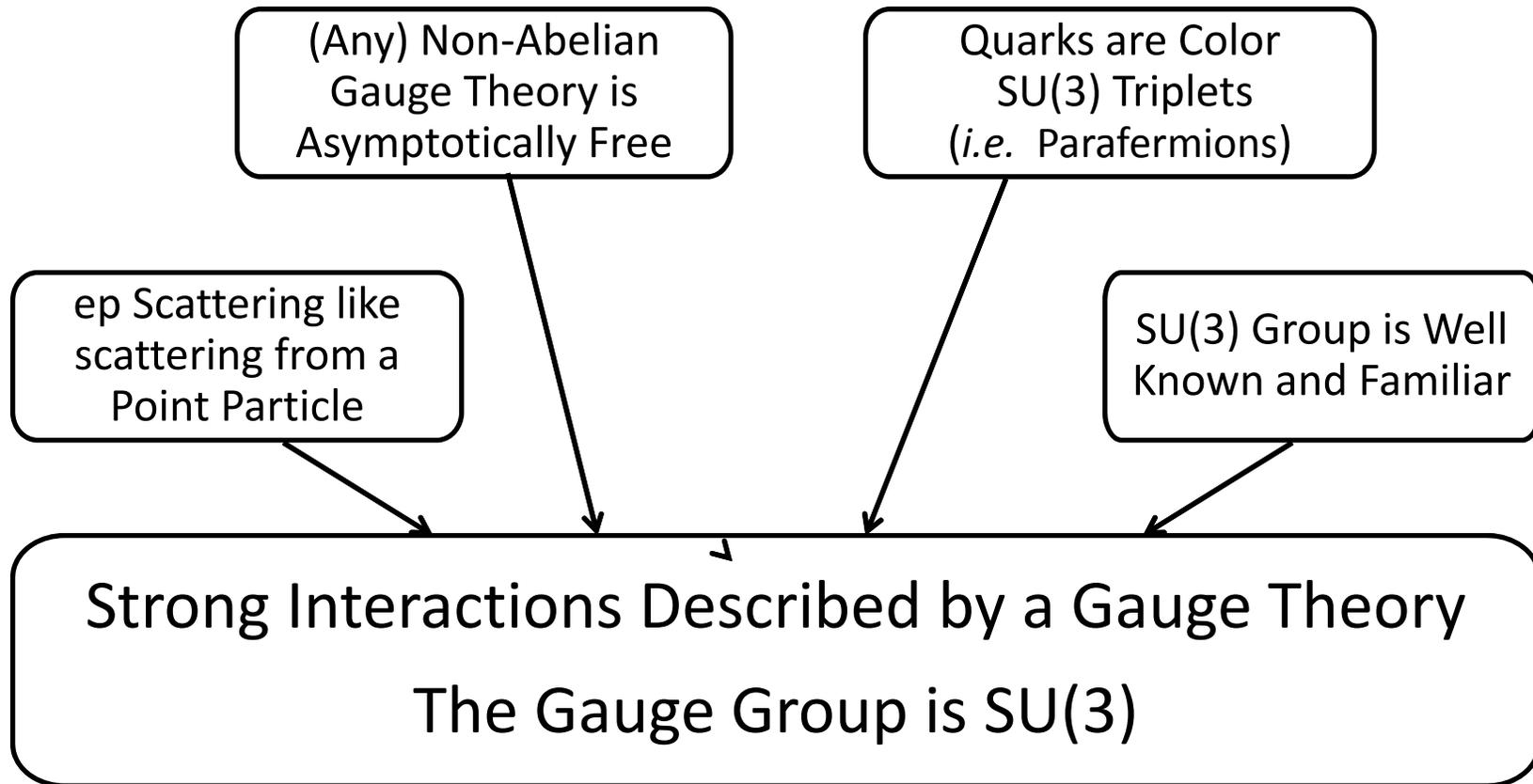
- Theory of Weak Interactions
 - Based on Yang-Mills Theory ['54]
and Higgs Mechanism [early '60s]
 - Renormalized after Several False Starts ['70]
 - Electroweak Force carried by Massive W^\pm, Z^0
- (Perturbative) Quantum Field Theory
 - Non-Abelian Gauge Theory Renormalized
 - Asymptotic Freedom Discovered
- Interpretation of Deep Inelastic ep Scattering
 - Protons Contained Pointlike Constituents (“Partons”)
 - Partons Conjectured to be the Quarks

1973: GETTING READY TO HATCH

QCD IDENTIFIED AS THE LONG-SOUGHT THEORY OF THE STRONG INTERACTIONS

- Asymptotic Freedom Justified Interpretation of Scaling as Scattering from Pointlike Quarks
- Gauge Theory Setting identified Strong Force as the Exchange of color \otimes gauge bosons [This is the Birth of Today's Gluon]
- Color morphs from mnemonic for 3 quarks in a baryon to the essence of the strong force
- Note: None of these developments came out of any elements of the quarks of 1964

ORIGIN OF THE IDEAS BEHIND QCD



“Overnight” Color Changes from a Mnemonic for 3 Quarks in a Proton to the Carrier of the Strong Force and Becomes the Heart of the Theory

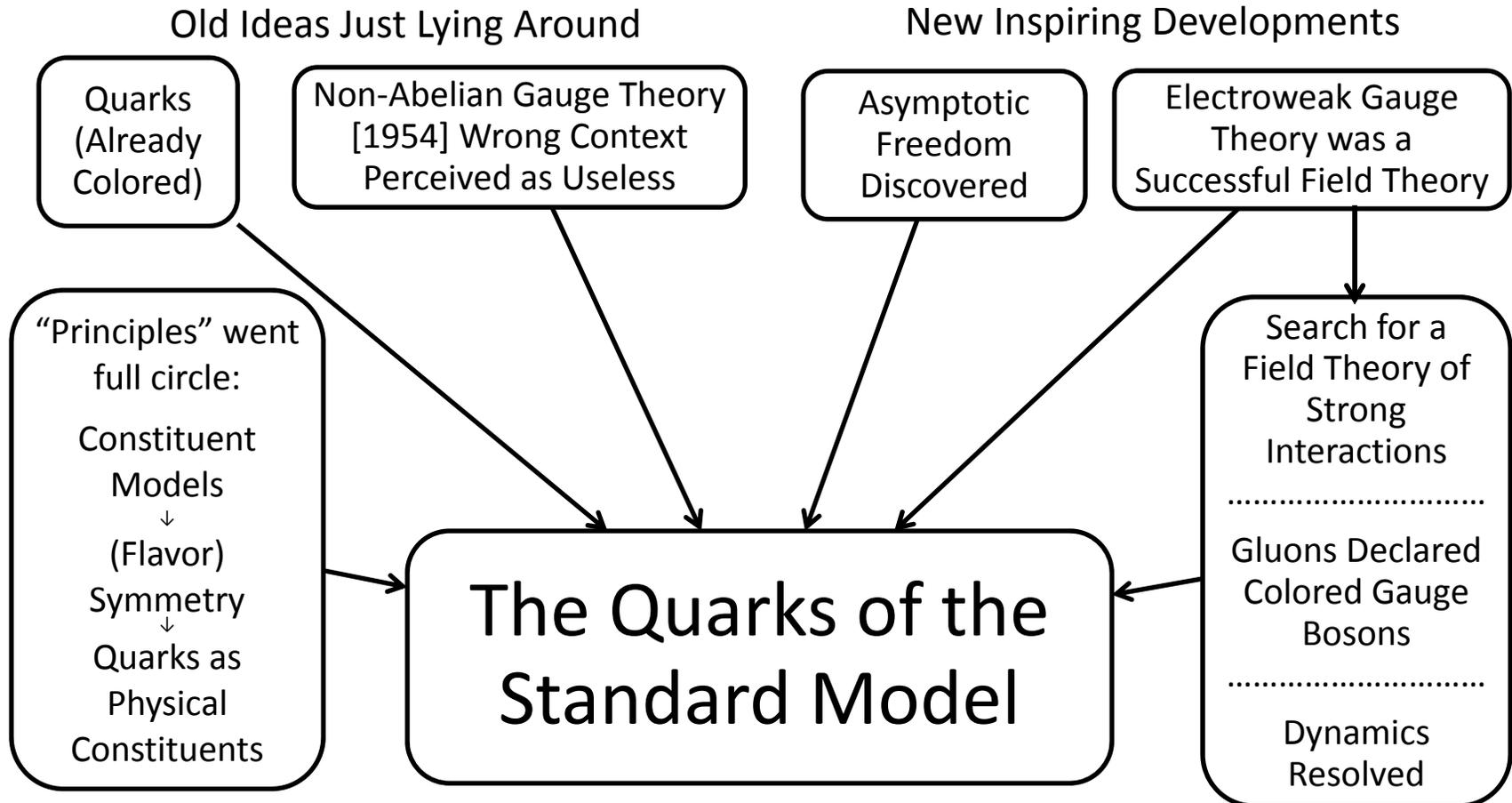
THE IMAGO WE NOW ADMIRE



The Color Octet Quark-Gluon Model of Strong Interactions

- SU(3) returns in a new context — Gauge Field
- SU(3) symmetry of 1964 quarks recognized as dynamical accident ($m_u \approx m_d \approx m_s \ll m_c \dots$)
- Symmetry that led to Quarks became irrelevant
- Progress now through Simulations

THE QUARKS OF QCD [1973]



SOME UNRESOLVED ISSUES

- Color vs Fractional Charge
- Color (Confinement)

Explains and Extends 1964 Rule

$$\# \text{ Quarks} - \# \text{ Antiquarks} = 0 \pmod{3}$$

- Does Not Explain Fractional Charge

Color is compatible with any quark charge

Sum Rules \rightarrow Quark Charges

OBSERVATIONS ABOUT THIS STORY

- QCD resembles the Quark Model as much as



resembles



- All key concepts preceded QCD by many years
- The relevant technology was known and ready to use, although invented in contexts where it was not successful

SOME SALIENT IRONIES

- SU(3) of the “Eightfold Way”
 - Not a Fundamental Property of Strong Interactions
 - Did not Directly Guide Discovery QCD Dynamics
 - Technology Facilitated Every Development
- Color
 - Comfortable Mnemonic for Parastatistics
 - Transmuted into Strong Interaction Gauge Group
- Fractional Charge
 - Came from Flavor SU(3) as a Basic Ingredient
 - Actually not Needed (by Strong Interactions)

LESSONS ABOUT THE RESEARCH ENTERPRISE

- Ideas and Techniques are Constantly Recycled
- This is Crucial for Rapid Progress
- Recognizing Correct Context to Apply an Idea is a Key Step — As important as the idea itself
- Evolution of ideas, *contra* their overthrow, preserves sense of intellectual continuity
- Importance of research depends on future use
- The flow of ideas and the process of absorbing them often governs the pace of progress