C.N. YANG IN THE HISTORY OF PHYSICS AND STONY BROOK

I. A towering figure of science

II. From Maxwell to Yang-Mills

III. His personal story & legacy at Stony Brook

C.N. YANG (1922 – 2025)

- A personal story inseparable from history: war-torn China to Chicago, IAS, Stony Brook and (back to) Tsinghua.
- A towering figure of science
- A symbol and statesman
- Opened areas of physics that will remain at the frontier far into the future.



I. A TOWERING FIGURE IN SCIENCE

Very quickly, first in words, then in
historic technical expressions

his three personal favorites . . .

OMNISCIENCE IN MODEL WORLDS



Wikimedia

- Precursor of modern science: Democritus (5th B.C.E) Lucretius (1st C.E): the world as "*Atoms and the Void*"
- Centuries later, Newtonian physics could compute everything in such a world "in principle" but with many "atoms", far too complex.
- Yang (1967): for a simplified model world (one dimension) we can compute the quantum mechanical future exactly for any number of "atoms".
- The Yang-Baxter Equation – the key to many such "solvable models". Influential in mathematics and tested with real atoms in 21st century.

SOME EXACT RESULTS FOR THE MANY-BODY PROBLEM IN ONE DIMENSION WITH REPULSIVE DELTA-FUNCTION INTERACTION*

C. N. Yang
Institute for Theoretical Physics, State University of New York, Stony Brook, New York
(Received 2 November 1967)

Yang-Yang thermodynamics on an atom chip

A. H. van Amerongen,[1] J. J. P. van Es,[1] P. Wicke,[1] K. V. Kheruntsyan,[2] and N. J. van Druten
[1] *Van der Waals-Zeeman Institute, University of Amsterdam, Valckenierstraat 65-67, 1018 XE Amsterdam, The Netherlands*
[2] *ARC Centre of Excellence for Quantum-Atom Optics, School of Physical Sciences, University of Queensland, Brisbane, Queensland 4072, Australia*
(Dated: October 23, 2018)

We investigate the behavior of a weakly interacting nearly one-dimensional (1D) trapped Bose gas at finite temperature. We perform *in situ* measurements of spatial density profiles and show that they are very well described by a model based on exact solutions obtained using the Yang-Yang thermodynamic formalism, in a regime where other, approximate theoretical approaches fail. We use Bose-gas focusing [Shvarchuck *et al.*, Phys. Rev. Lett. **89**, 270404 (2002)] to probe the axial momentum distribution of the gas, and find good agreement with the *in situ* results.

A keystone for the concept of integrability, from "delta function gas" to N=4 SYM.

VOLUME 19, NUMBER 23 PHYSICAL REVIEW LETTERS 4 DECEMBER 1967

SOME EXACT RESULTS FOR THE MANY-BODY PROBLEM IN ONE DIMENSION WITH REPULSIVE DELTA-FUNCTION INTERACTION*

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The repulsive δ interaction problem in one dimension for N particles is reduced, through the use of Bethe's hypothesis, to an eigenvalue problem of matrices of the same sizes as the irreducible representations R of the permutation group S_N. For some R's this eigenvalue problem itself is solved by a second use of Bethe's hypothesis, in a generalized form. In particular, the ground-state problem of spin-$\frac{1}{2}$ fermions is reduced to a generalized Fredholm equation.

(1) Consider the one-dimensional N-body problem

$$H=-\sum_{1}^{N}\partial^2/\partial x_i^{\,2}+2c\sum_{i<j}\delta(x_i-x_j),\quad c>0, \tag{1}$$

with no limitation on the symmetry of the wave function ψ. For a given irreducible represen-

with the aid of the following identities:

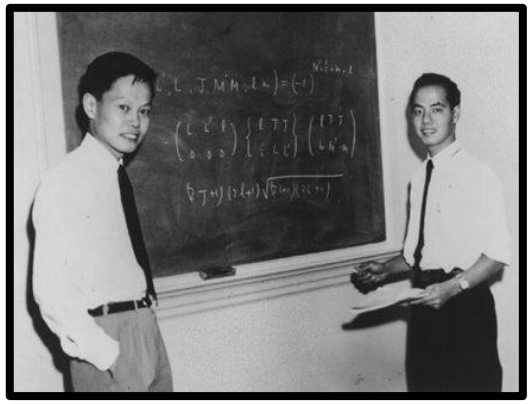
$$Y_{ij}^{\,ab}Y_{ji}^{\,ab}=1, \tag{7}$$

and

$$Y_{jk}^{\,ab}Y_{ik}^{\,bc}Y_{ij}^{\,ab}=Y_{ij}^{\,bc}Y_{ik}^{\,ab}Y_{jk}^{\,bc}, \tag{8}$$

A TWIST TO THE UNIVERSE: PARITY VIOLATION

- Imagine a video of particles undergoing radioactive decay.
- Could we tell if that video was taken directly or in a mirror? Until 1956, the answer was assumed to be “no”. How could laws of nature know about that?
- In 1956, with Tsung-Dao Lee, C.N. Yang discovered that puzzling decay patterns could be explained if the answer were “yes”. Parity symmetry is violated -- the thunderbolt announcement by experimentalist C.S. Wu, January 1957.
- Lee and Yang: Nobel Prize for Physics, 1957



NIST



Phys.World

To pose the question:

. . . and identify the simplest of criteria to answer it.

. . . And to realize that nature invites our interrogation for other symmetries.

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

To be more specific, let us consider the allowed β transition of any oriented nucleus, say Co^{60}. The angular distribution of the β radiation is of the form (see Appendix):

$$I(\theta)d\theta = (\text{constant})(1+\alpha\cos\theta)\sin\theta d\theta, \qquad (2)$$

where α is proportional to the interference term CC'. If $\alpha \neq 0$, one would then have a positive proof of parity nonconservation in β decay. The quantity α can be

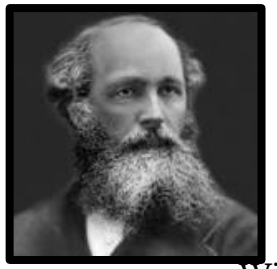
A SYSTEM FOR OUR WORLD

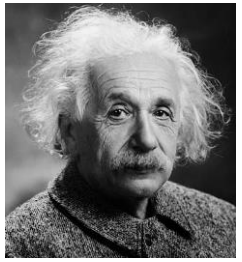
Theories of Newton (1696) and Einstein (1915) describe gravity, those of Faraday and Maxwell (1865) describe electricity and magnetism.

The discovery of radioactivity (1896) and the atomic nucleus (1911) give two "new" forces: a "strong force" that holds nuclei together a "weak force" that produces radioactive decay. Together, they make the sun shine.

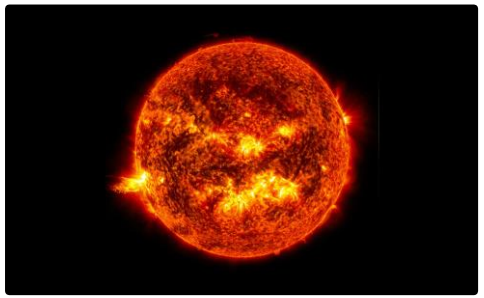
Yang-Mills Theories were developed on sabbatical at Brookhaven National Laboratory (1954). "The idea was beautiful and should be published."

Subsequent decades have shown that the weak and strong force are both described by Yang-Mills theories.





Wikipedia, Wikimedia



NASA



At Stony Brook, 1999

An inspiration in tangible physics . . .

The two extra terms generate new worlds.

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. YANG † AND R. L. MILLS
Brookhaven National Laboratory, Upton, New York
(Received June 28, 1954)

$$F_{\mu\nu}=\frac{\partial B_\mu}{\partial x_\nu}-\frac{\partial B_\nu}{\partial x_\mu}+i\epsilon(B_\mu B_\nu-B_\nu B_\mu).$$

Yang described this as his greatest contribution, and most would agree.

The symmetry dictates the interactions.

The story of particle physics to the mid-1980's was the creation of the Standard Model as the gauge theory SU(3)_strong x (SU(2) x U(1))_electroweak.

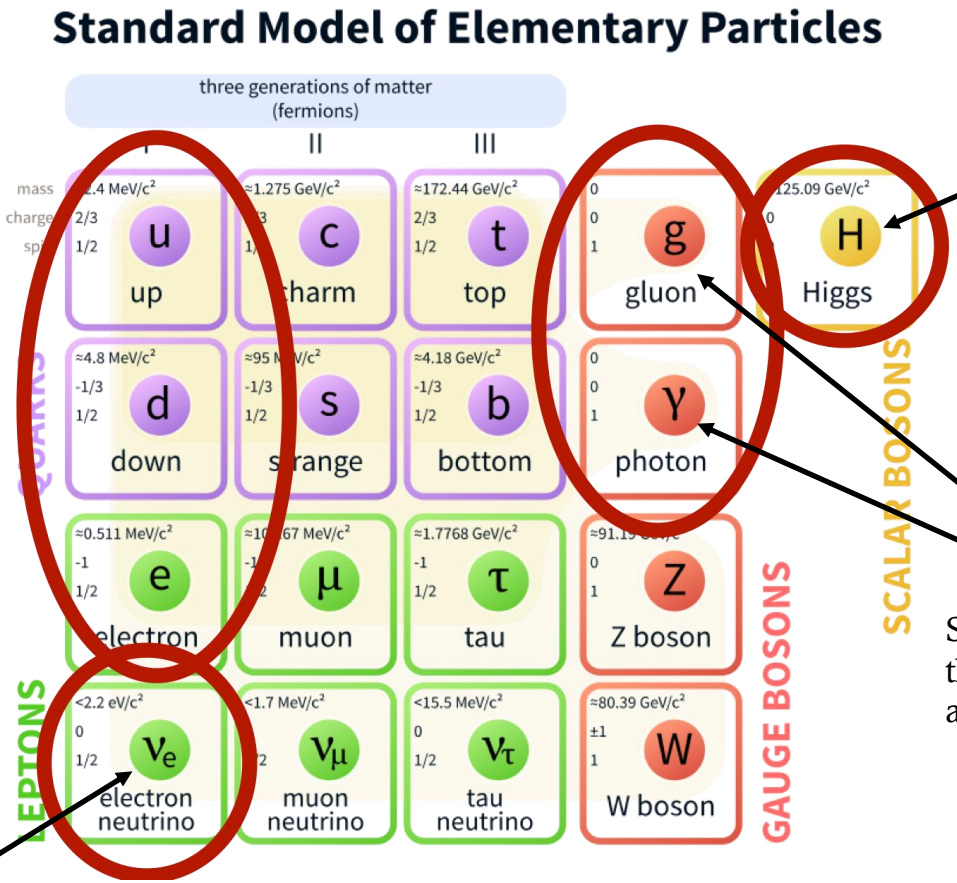
Twentieth Century Theory Foundations

- 1971: **Renormalizing** nonabelian gauge quantum field theory (G. 't Hooft & M. Veltman)
- 1961 – 1967: For electroweak interactions, the formulation of **symmetry breaking** in SU(2)xU(1) (S. Glashow, S. Weinberg, A. Salam)
- 1973: For the strong interactions, **asymptotic freedom** (D. Gross & F. Wilczek, D. Politzer)
- 1974 – 1983 **Lattice gauge theory** verification of confinement spectra and low energy SU(3) dynamics (K. Wilson, M. Creutz . . .)
- 1975 -- **Infrared safety and perturbative QCD** jets factorization (GS & Weinberg, Mueller, Brodsky, Collins & Soper . . .)

HERE'S A SUMMARY, STARTING WITH The"everyday" particles.

Everything we see contains these

(uud) forms a proton, (udd) a neutron.



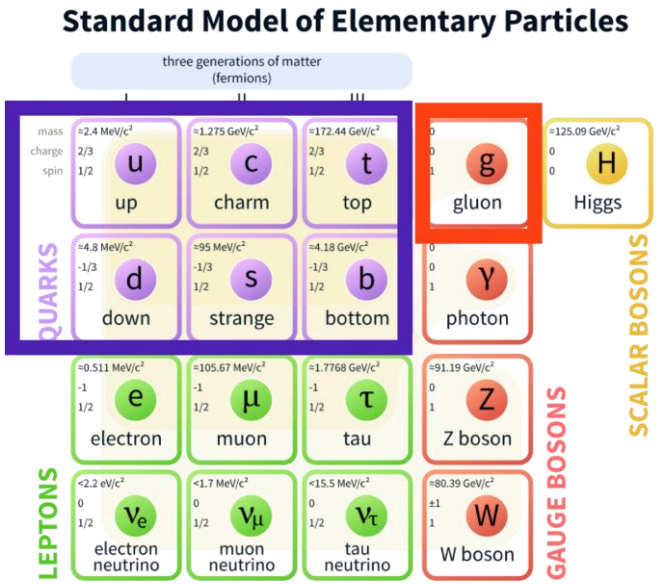
Literally everywhere but unseen

Supply the forces that hold nuclei and atoms together

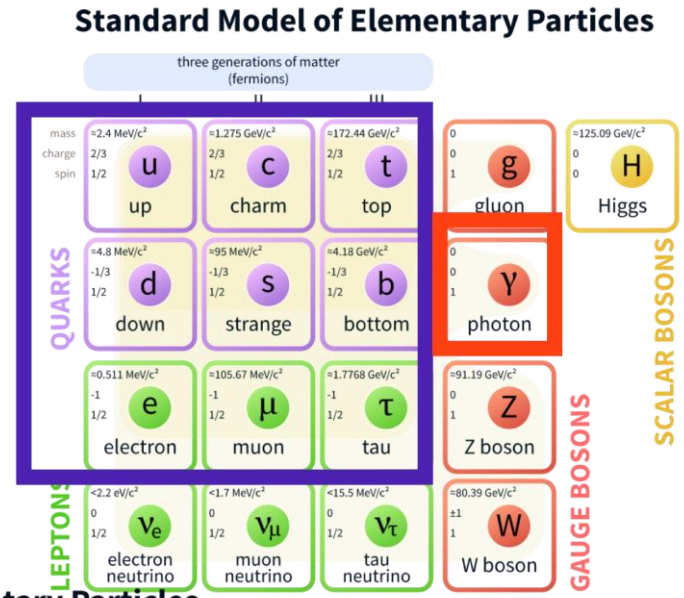
Don't usually see them but they're all over the place

FORCES

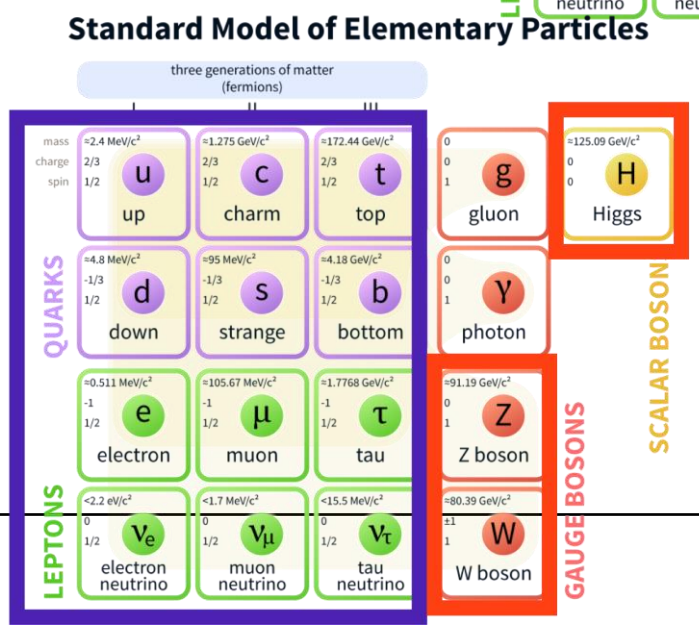
The strongly interacting fermions & their gluon (QCD):



The charged fermions & their photon (QED):



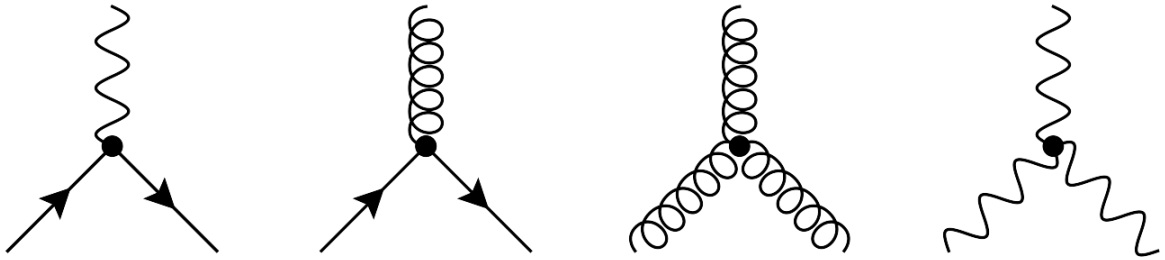
All the fermions experience the weak force:



Here are the rules for the electromagnetic, strong and weak forces. They are each proportional to a "charge": electric: e, strong: g_s, or weak: g_W.

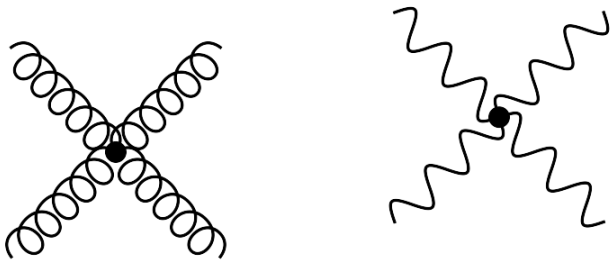
Yang-Mills theories (1954) for the strong and weak interactions - charged vector particles.

Rules for three particles



charge e | charge g_s | charge g_s | charge gw

Rules for four particles

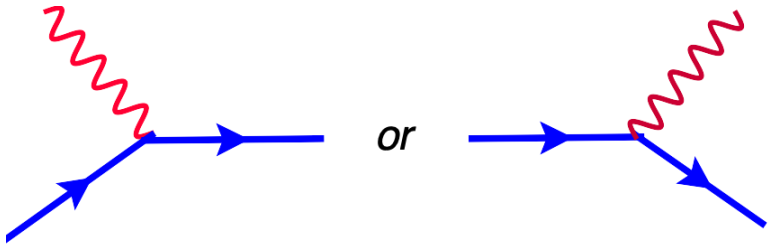


charge $(g_s)^2$ | charge $(gw)^2$

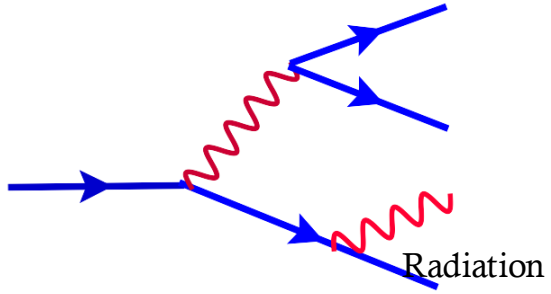
All time directions are allowed.

Here's how it works:

There is a kind of restlessness in nature: very single particle
is constantly trying to unwind a whole new world out of itself,
and at the same time to ravel it back up,
always through simple steps that increase or decrease
the number of particles by one or two.



And it keeps going on and on.

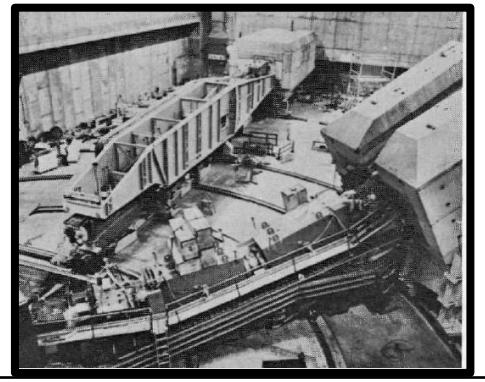


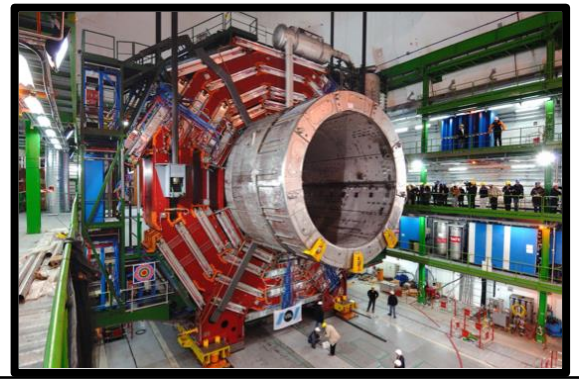
Pair creation - particle
and antiparticle
(same mass opposite
charge(s))

Accelerator Milestones

- 1969: Observation of **point charges** in deep-inelastic electron-proton scattering
- 1973: Observation of **weak neutral currents** (exchange of a heavy photon partner)
- 1983: Discovery of the **W and Z bosons** (SU(2)xU(1))
- 1975 – 1979: Observation of **quark and then gluon particle jets** (SU(3))
- 1983 - 1984: jets from **quark-quark and gluon-gluon scattering**.
- 1977 – 1995: The discovery of **heavy quarks and leptons** that allow self-consistent (anomaly free) quantization with CP violation.
- 2012: The **Higgs boson** as the agent of symmetry breaking
- Then until now: the dawn of **precision at the highest energies** in pursuit of physics beyond the Standard Model.

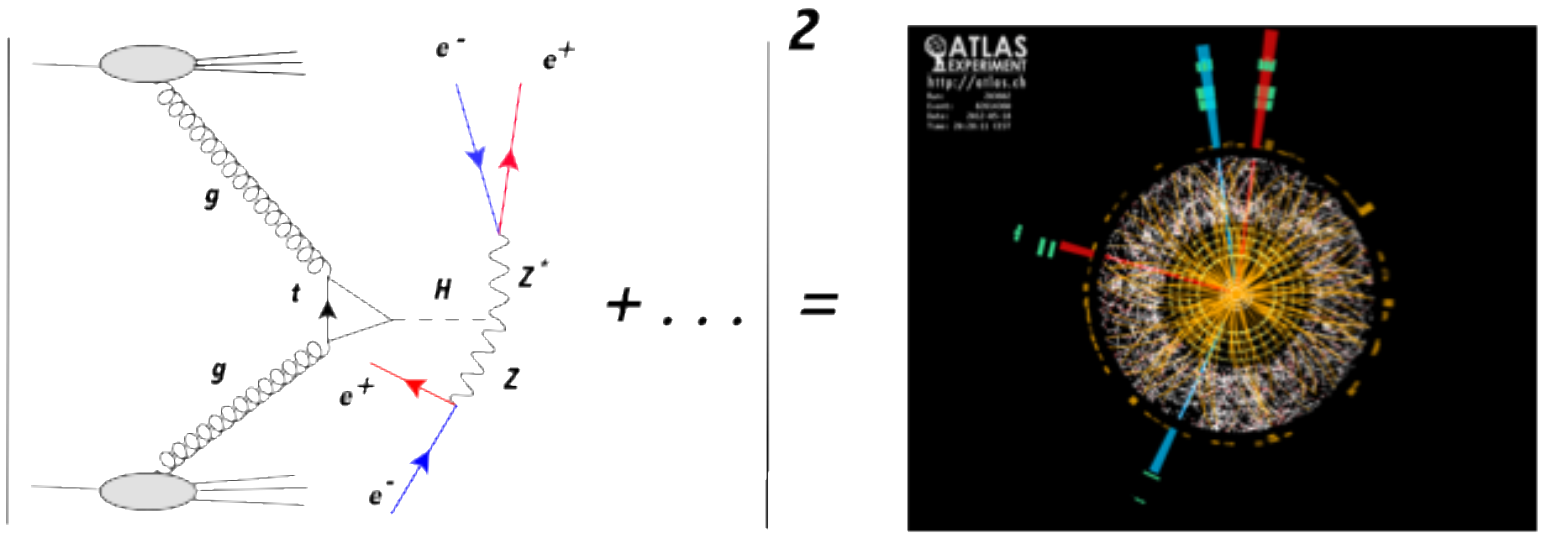
SLAC, 1969
'Blue book'





CMS
Brittanica

We can sum it up with a picture worth a thousand words:



From $SU(3)$ color through the Higgs into $SU(2)_L \times U(1)$.

Every observed final state is the result of a quantum-mechanical set of stories, and so far the stories supplied by the Standard Model, built on an unbroken $SU(3)$ color gauge theory (very much like the original Yang-Mills Lagrangian) and a spontaneously-broken $SU(2)_L \times U(1)$, account for all observations at accelerators.

A Future Beyond the Standard Model

This History Is Still Writing Itself. The Need Is Clear.

- **From observation: a "dark" universe - dark matter and energy.**
- **From theory "aesthetics": the instability of quantum corrections involving the Higgs boson. And where did this version of electroweak symmetry breaking come from? How do we get just this list of leptons and fermions?**

***None of this implies a limitation of gauge theory*. Possibly it's** arger groups; "Grand Unification", Alternative symmetry breaking scenarios, Supersymmetry and Supergravity, String theory.

All designed incorporate and/or generate gauge theories of the Standard Model.

II. From Maxwell to Yang-Mills

- **A. Introduction: From Light to Quantum Waves**
- **B. Quantum Waves and Phases**
- **C. Phase Invariance**
- **D. The Yang-Mills Construction**

A. Introduction: from light to quantum waves

- The 19th Century saw the unification of electricity and magnetism (E&M), and the realization that light is a wave of these fields together.

- E&M was the first gauge field theory, characterized by transverse waves and charge conservation.

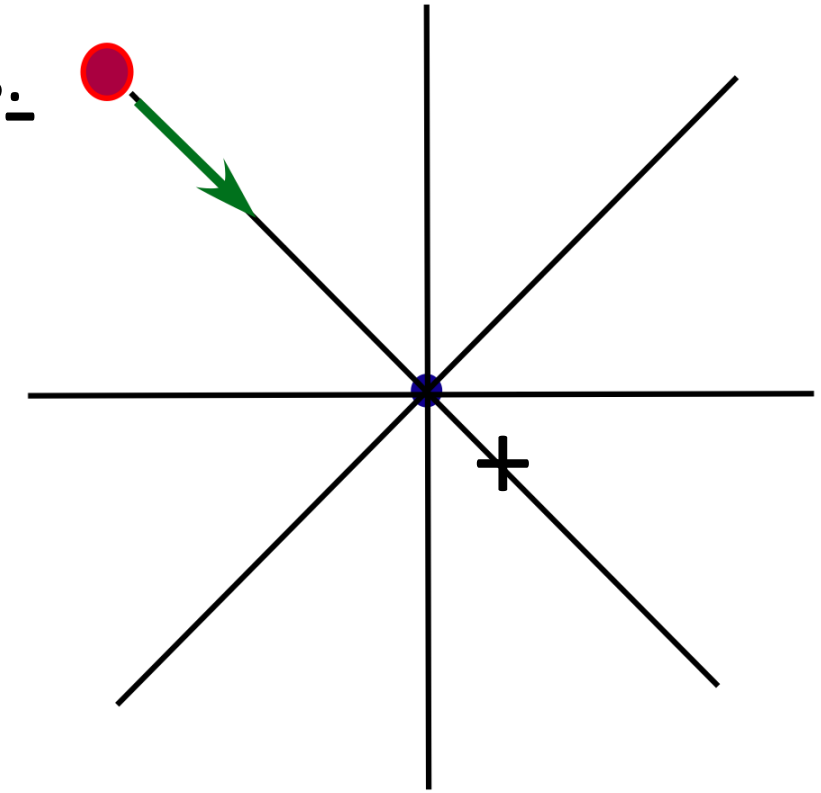
- The density of photons is proportional to the square of the E&M wave amplitude.

- Light and electrons can both be described as particles with wave-like properties, but light is created and absorbed “at a point”

The 19th C, in brief

- From John Dalton, 1810: multiple proportions (like H_2O)
- Michael Faraday: mass/charge for hydrogen ion.
- J.J.Thompson, 1897: discovery of the electron
- And from Maxwell, 1865:
- light and electromagnetism . . . starting with “plus & minus“.

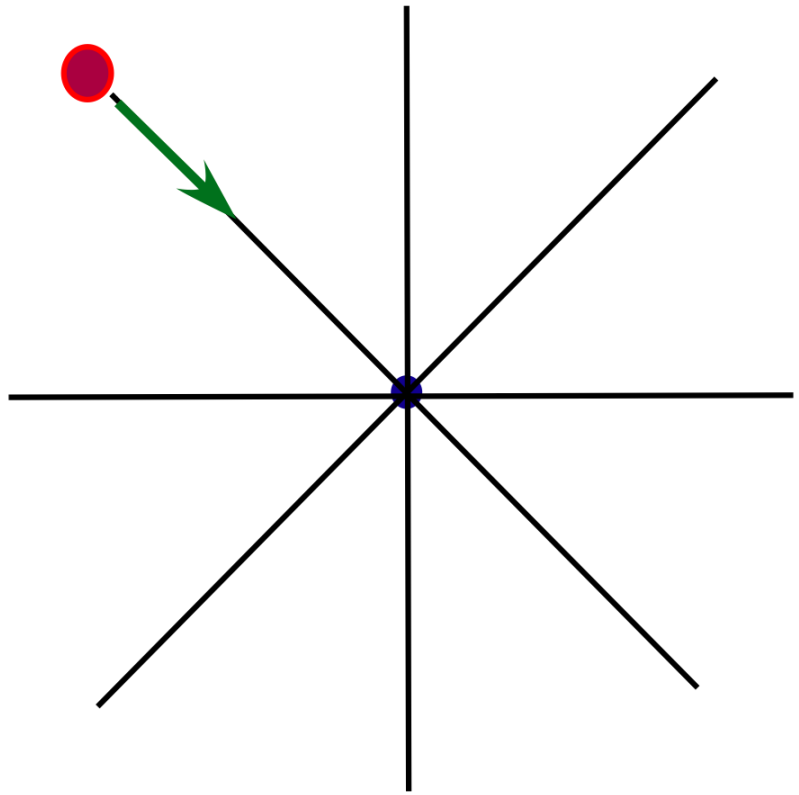
Lines of force around an immovable plus charge guide nearby minus charges.

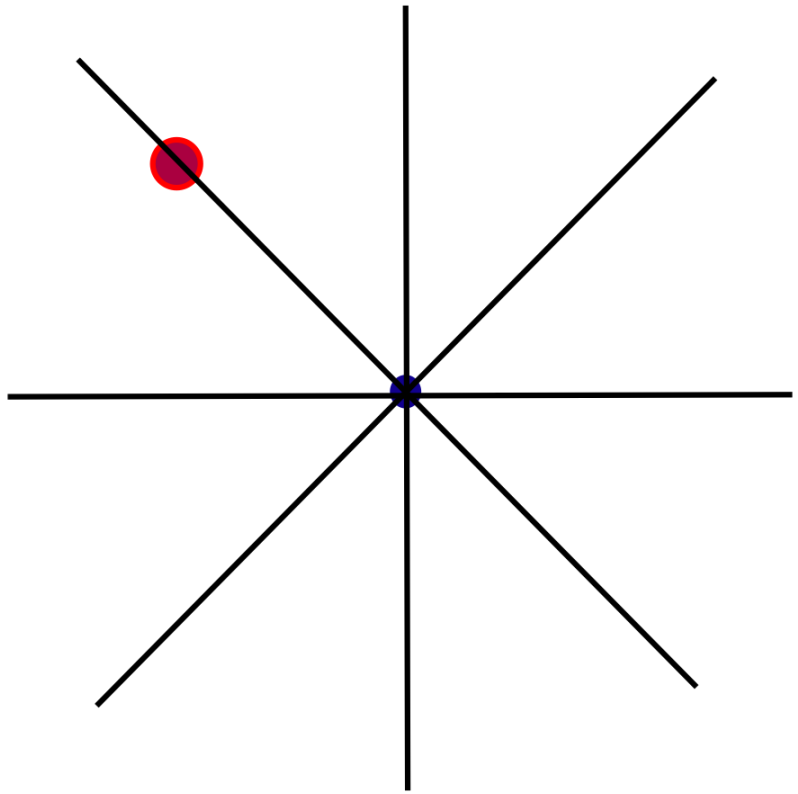


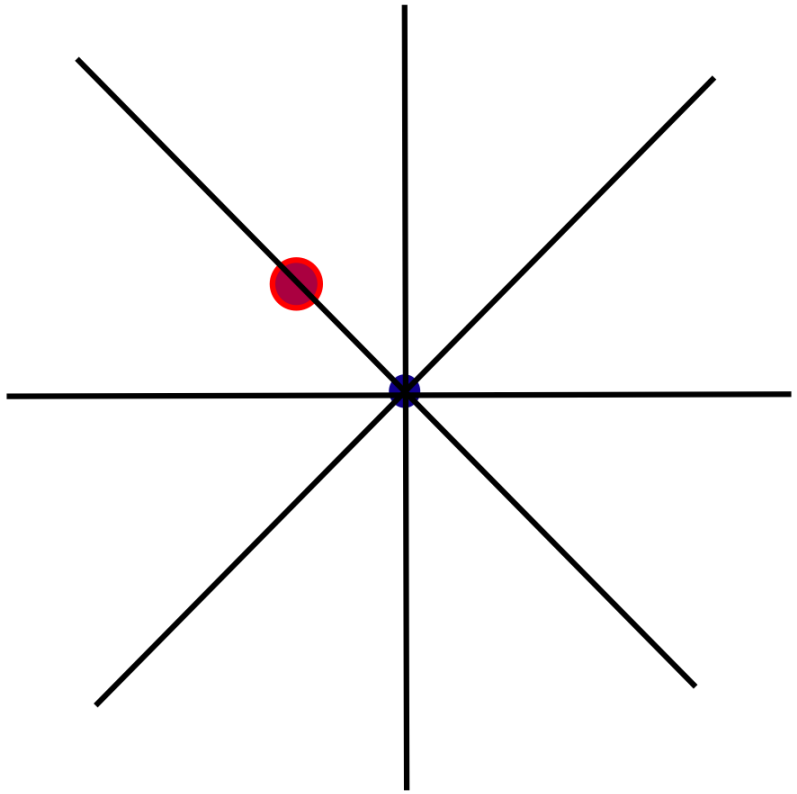
Michael Faraday, William Thomson, 1830--1860

Something seems to be in between.

It’s not “action at a distance”.





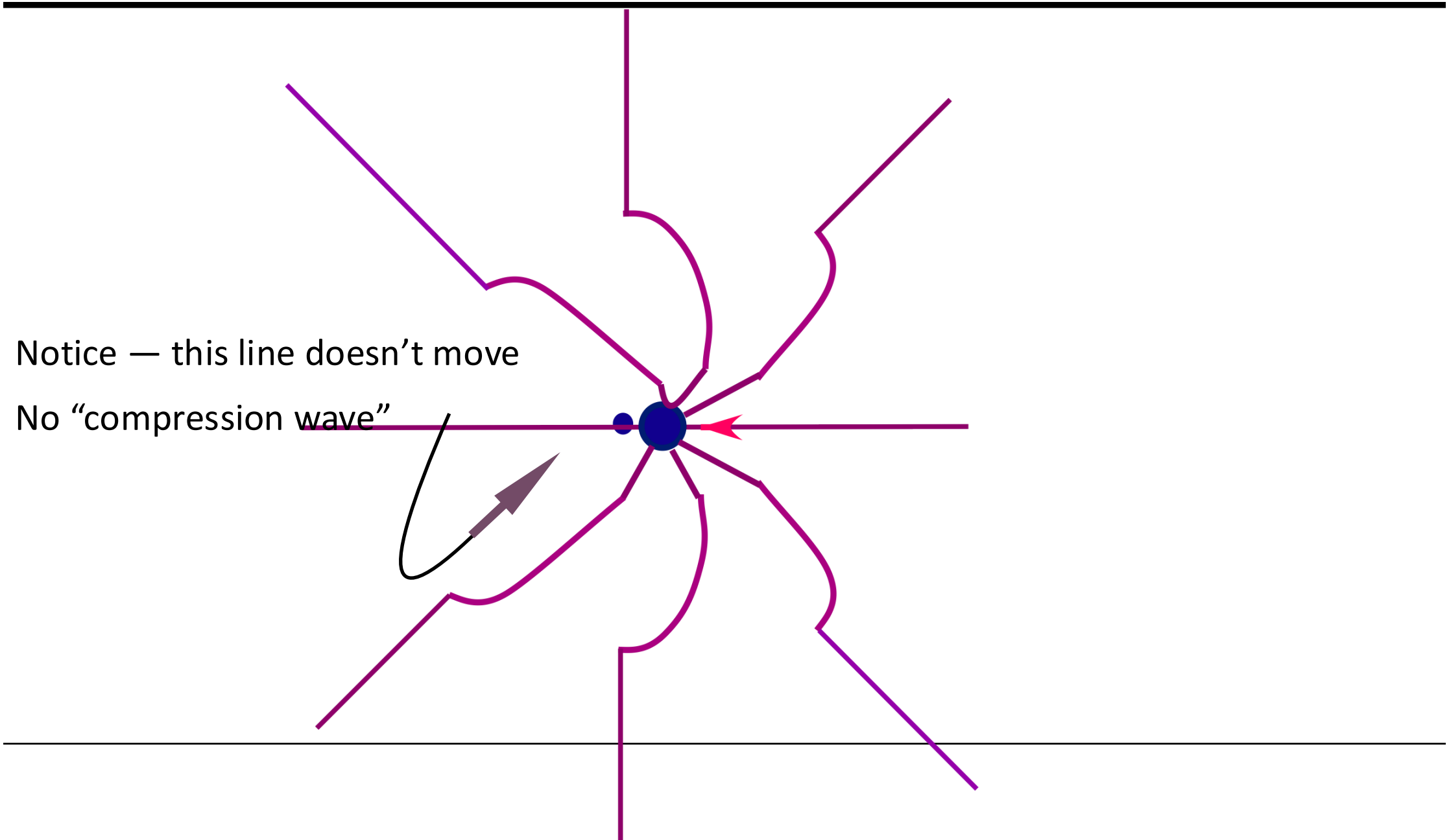


Do these “lines of force” correspond to something real ?

Faraday, Thomson & Maxwell: yes.

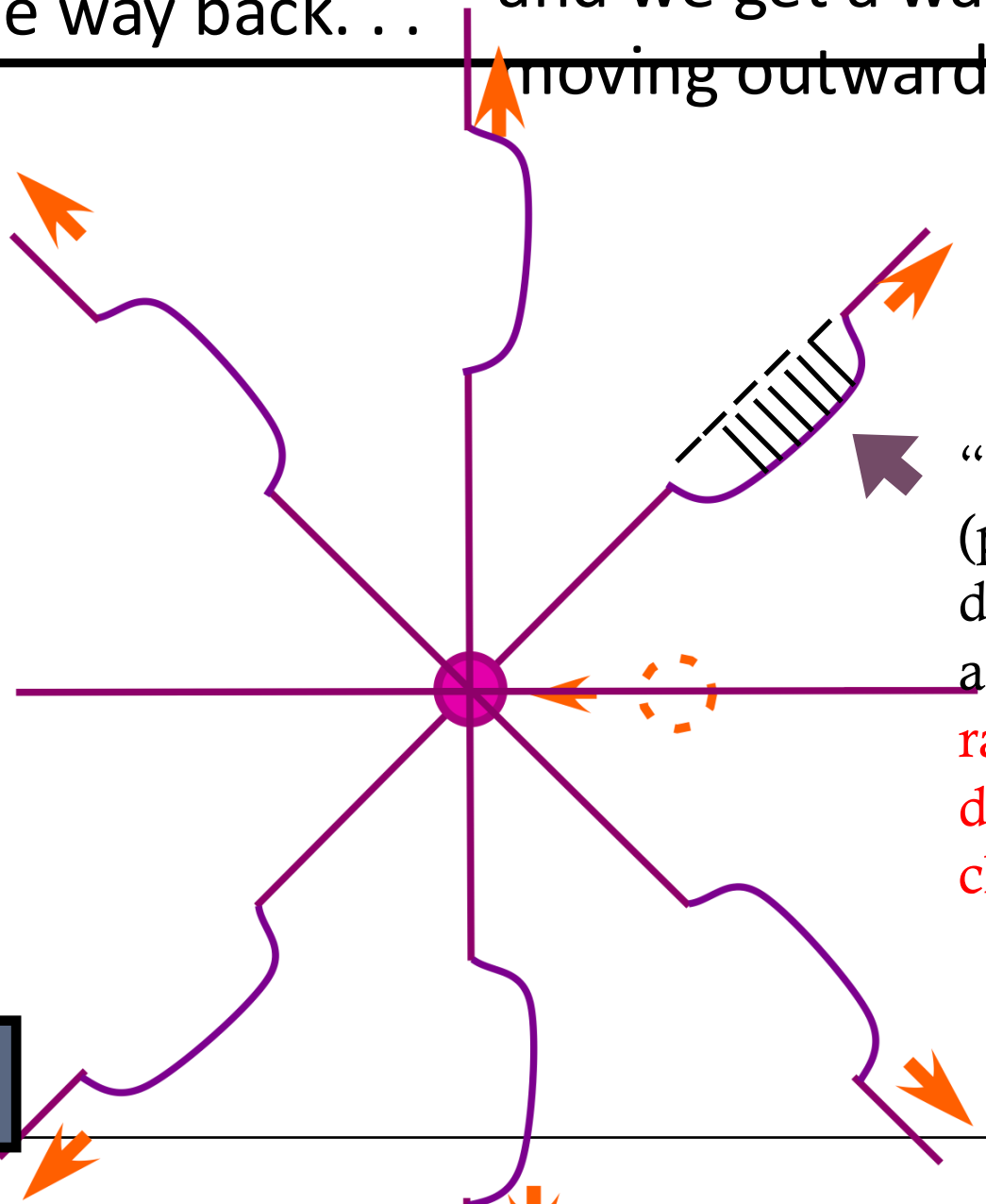
The **electric field.**

And back. Lines start to move back



All the way back. . .

and we get a wave in the lines moving outward.



"Transverse" (perpendicular) displacement. and no radiation in the direction the charge moves.

Hertz:

These waves move electrons in wires. . . Radio !

What Maxwell Found

When the wave moves out, a magnetic field appears along with it. “Radiation”. In fact:

Electric force measured by a constant k
Magnetic force measured by a constant μ

Speed of light: c = 300,000 km/sec

$$c^2 = k/\mu$$

c squared = (Electric constant) / (Magnetic constant)

Unification of forces

ELECTROMAGNETISM AS THE FIRST GAUGE THEORY

- Maxwell's waves are all "transverse", vibrating perpendicular to their direction of motion.

- The absence of waves in the direction a charge oscillates is connected to the conservation of electric charge. If we compress the wave, it looks like the charge is closer than it is.

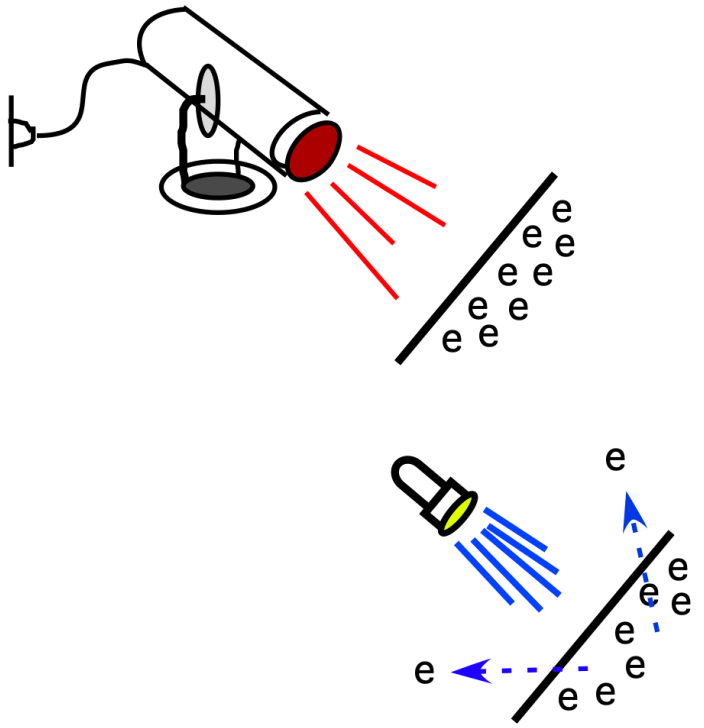
- Theories with charge conservation and only transverse waves are "gauge theories". Electromagnetism was the first.

- The energy carried by waves is proportional to the square of the fields:

$$\text{Energy density} = \text{constant} \times (\text{Electric field})^2$$

- The "compression" light waves don't contribute to the energy.

Meanwhile, around 1888, in his wave experiments,
Hertz also
noticed: The Photoelectric Effect



Even a little blue light knocks electrons out of metals.
Even intense red light doesn't knock them out at all.

Einstein (1905):

- Waves are the correct description of light for "time averages", but the "creation and conversion of light" requires a particle description.

- Light waves consist of a collection of photons. Electrons are only knocked out by one photon at a time, and blue photons have more energy than red. Photons are the "force particles" of E&M.

To be more precise . . .

Photon energy = h x (frequency of the wave) = hn

h = Planck constant

h / 1 sec. = 6.6×10^{-34} (Joule = 1 Watt x 1 sec)

or about
250,000,000,000,000,000 photons per second
for every watt of a light bulb (visible light).

$$\text{Photon density} = \frac{\text{Energy density of wave}}{\text{Energy for one photon}}$$

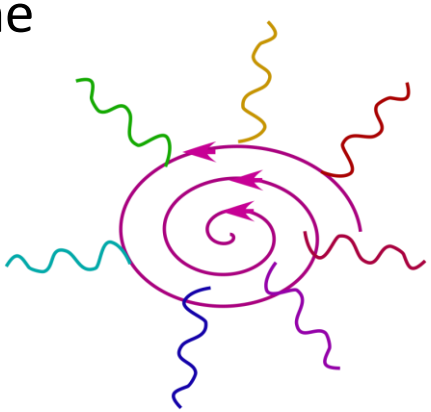
$$\text{Photon density} = \frac{\text{constant x (Field)}^2}{\text{hn}}$$

B. Quantum Waves and Phases

- And that's not all . . . not only the photon of light, but **the electron is also a wave.**

- A picture like this was necessary once the atomic nucleus was discovered (Rutherford et al.). Here's why:

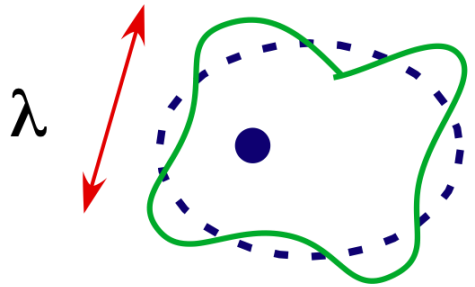
- We've seen that oscillating charges radiate. In E&M, atoms would collapse in a burst of light, as all electrons spiral into the nucleus. Luckily, this is not observed in nature.



Solution: 1909 . . . 1926

Bohr -- de Broglie -- Heisenberg -- Schroedinger

Electrons are waves too !



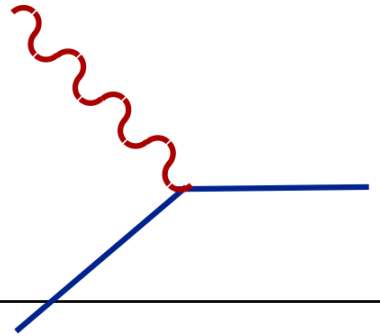
Electrons don’t spiral in, because the waves can’t fit !

l = h / p, the “de Broglie wavelength”

The waves of light and electrons have a reality all their own. They exist as themselves in space, with no intermediary “ether”. They are called collectively, “fields”, yet they interact as particles.

When described in terms of particles, one electron is ejected from a metal when it absorbs one photon “at a point”

like this:



C. Quantum Waves and Phases

But Quantum Waves are different!
We cannot directly observe their peaks and valleys, their "phase".
So this wave:



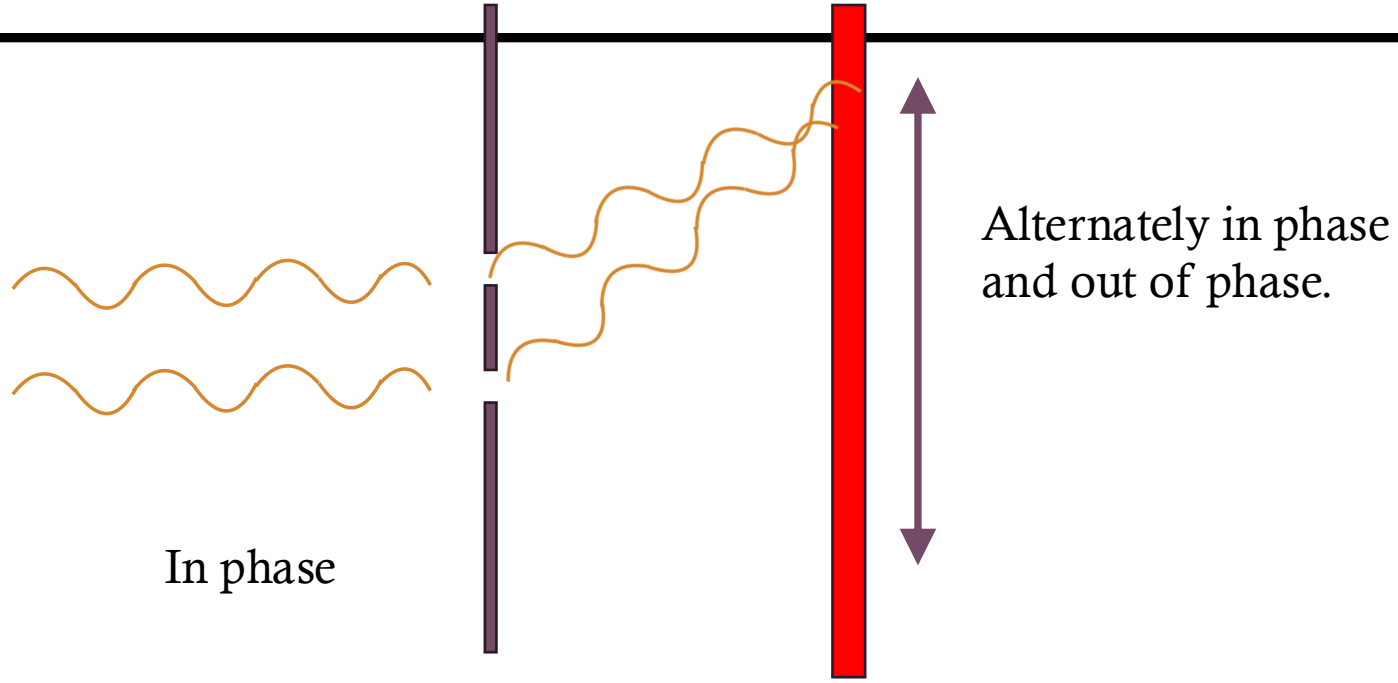
Gives the same experimental predictions as this wave:



But if you combine them, these two wave cancel! So differences can be observed: "interference experiments". These two are "180 degrees out of phase".

Doesn't seem like much, but following this idea explains the visible universe!

The ”double-slit” experiment

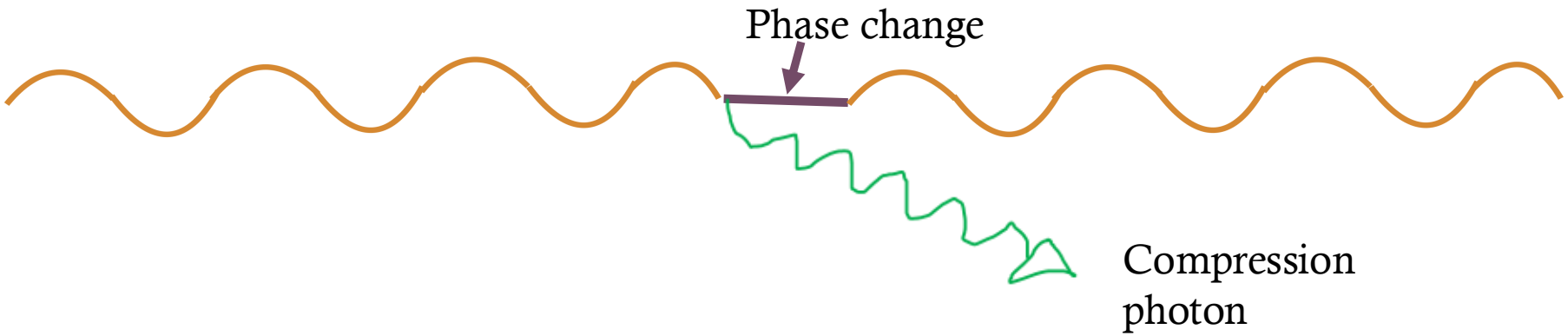


A matter wave can interfere with itself, even though it corresponds
To just one particle (photon, electron . . .) at a time

(Video from Wikipedia here)

Yang and Mills start from here: "A change in gauge means a change in phase . . . that is devoid of any physical consequences"

But it had been noticed, you can change the phase of a line by emitting an "unphysical compression wave". A phase change is like a hesitation in the direction of the wave: just the direction a compression wave would go!



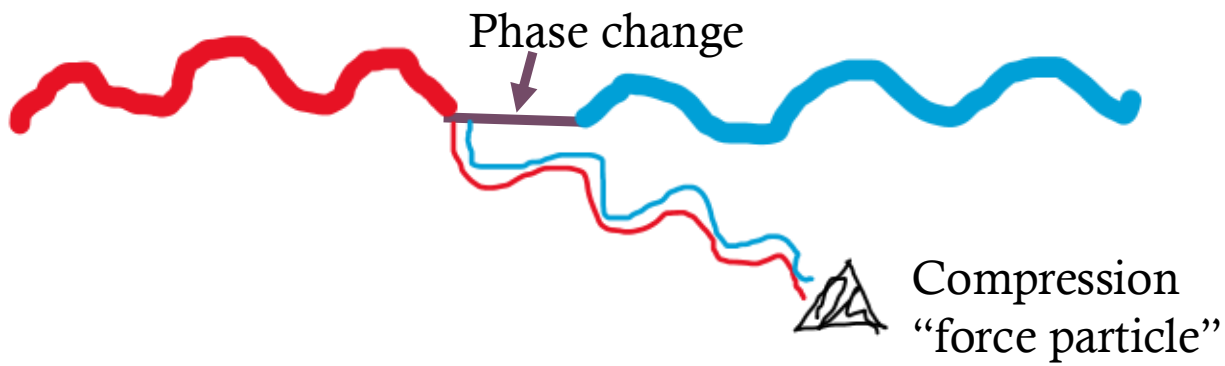
Neither is directly observable, but they cancel. **Seems sort of abstract**. How important is this?
If you didn't know there were physical photons with transverse waves you could have predicted them!

D. The Yang-Mills Construction

Inspired by data about protons and neutrons, Yang and Mills asked whether this picture could apply to a system of particles with more than one "charge".

Could we have a gauge theory based on two kinds of matter waves? Let's say the waves have different "colors".

Just as with a single charge . . .
you can change the phase and color of a line by emitting an "unphysical compression particle". Like a compression photon, but now
the unphysical wave has to carry combinations of the color charges.



Neither the phase nor the compression particle is directly observable in our new theory, but they still cancel.

But, to make it a theory, you still have to figure out how to predict new transverse waves
in a way that doesn't let the compression
waves contribute to the energy. THIS is what Yang and Mills did. The hardest part was identifying
The correct energy for the gluons that doesn't allow compression gluons.

And that's what this does, leading eventually
To the Standard Model.

$$F_{\mu\nu} = \frac{\partial B_\mu}{\partial x_\nu} - \frac{\partial B_\nu}{\partial x_\mu} + i\epsilon(B_\mu B_\nu - B_\nu B_\mu).$$

- The three historic papers highlighted above have in common their brevity, elegance and clarity. And their consequences are far-reaching
- Freeman Dyson described C.N. Yang as, along with Einstein and Dirac, one of the “preeminent stylists of twentieth century physics.”
- Yang wrote that his style was in large part the product of his early education.

III. HIS PERSONAL STORY AND LEGACY HERE

How did all this come about?

Yang described his own professional development and research philosophy at considerable length:
C.N. Yang, *Selected papers* (1980) and
Selected Papers II (2013) offer recollections and interpretation.

FROM CHILDHOOD TO WARTIME

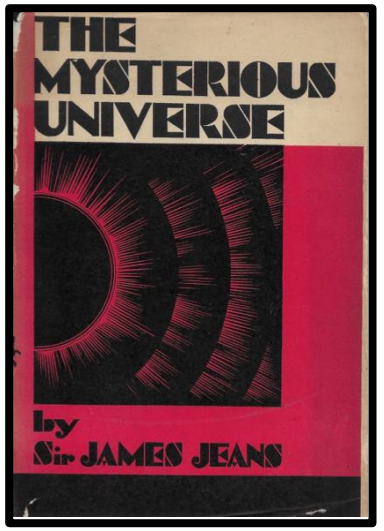
Chen Ning Yang was born in Hefei, Anhui Province, China, in 1922. His father studied mathematics in the U.S. (Chicago, 1928) and moved with his family to Tsinghua University, Beijing (1929)

Frank describes growing up and his early education in *Father and I.* In many ways his youth in Tsinghua was idyllic.

"**When I was nine or ten years old**" his father "**observed I was gifted in mathematics**" but there was no rush. Summer studies concentrated on works of the Confucian philosopher Mencius. At twelve, he was much impressed by *The Mysterious Universe,* a popular account of modern physics by Sir James Jeans.

But when Yang was 14, in July, 1937, only 20 km away the "Marco Polo Bridge Incident" led to war with Japan. Beijing fell within a month. The family fled.





Wikipedia

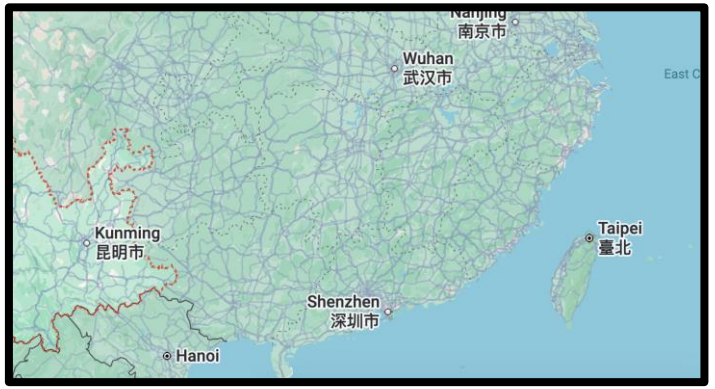


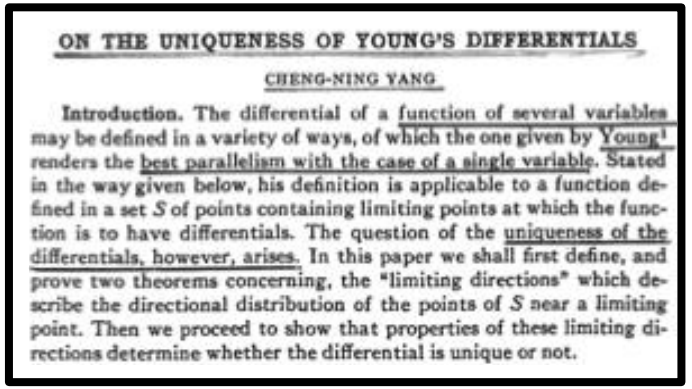
Wikipedia

SOUTHWEST ASSOCIATED UNIVERSITIES



- 1938: enrolled at the displaced National Southwest Associated University in remote Kunming, Yunnan Province: a powerhouse combination of Tsinghua, Peking and Nankai university faculty
- By no means fully removed from ongoing hostilities. "**there were air raids and there were air raids**." Yet not cut off from world of science.
- 1944: Master of Science under T.Y. Wu . . . "**in retrospect I am deeply grateful**". Two publications by 1944 based on master's thesis: in *Bull. Amer. Math. Society* and *Journal of Chemical Physics.*
- "**my taste in physics was largely formed during the six years . . . I was a student at Kunming** . . . [I learned] **to admire the work of Einstein, Dirac and Fermi . . . to zero in on the essentials.**" Symmetry!





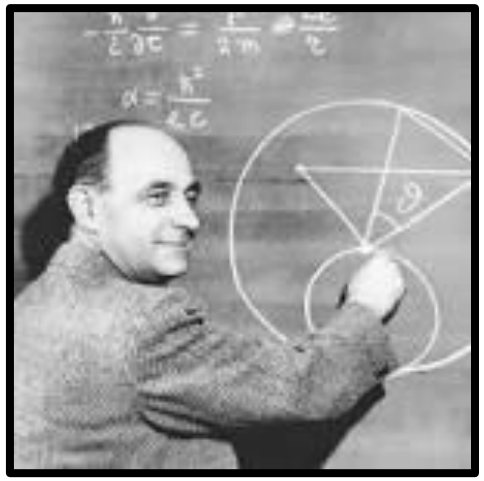
ON THE UNIQUENESS OF YOUNG'S DIFFERENTIALS

CHENG-NING YANG

Introduction. The differential of a function of several variables may be defined in a variety of ways, of which the one given by Young[1] renders the best parallelism with the case of a single variable. Stated in the way given below, his definition is applicable to a function defined in a set S of points containing limiting points at which the function is to have differentials. The question of the uniqueness of the differentials, however, arises. In this paper we shall first define, and prove two theorems concerning, the "limiting directions" which describe the directional distribution of the points of S near a limiting point. Then we proceed to show that properties of these limiting directions determine whether the differential is unique or not.

CHICAGO

- A fellowship brought him to the Chicago in 1945, seeking to work with Enrico Fermi. Much later, describes Fermi as a "perfect Confucian gentleman."
- Enrolled in January 1946. "**I had wanted to write an experimental thesis** …" But in the lab, "**where there is a bang, there is Yang**"
- "**. . . when my experiment [20 months] did not go well Teller suggested I abandon my plan and said he would sponsor [a completed projecct] as my thesis. I was at first disheartened but in a few days recovered and accepted his suggestion with relief.**"
- Research on nuclear and then particle physics. Meets T.D. Lee.
- Graduated June 1949. Stayed into 1950, wrote his only paper with Fermi.





THE INSTITUTE FOR ADVANCED STUDY



IAS

- Fermi and Teller wrote to Oppenheimer, and Yang took a one-year postdoc at the Institute for Advanced Study in Princeton in the fall of 1949, with the expectation that he would return to Chicago.
- "**Fermi advised that I should go for a year, but not more . . . the physics is too abstract**" Don't stay in the "Ivory Tower".
- In 1950, choice to return or stay: "**I decided to stay on at the Institute because I was dating Chi Li Tu, who was then studying in New York City.**" This choice worked out well in every sense.
- And, as we know, Frank eventually left the Ivory Tower.

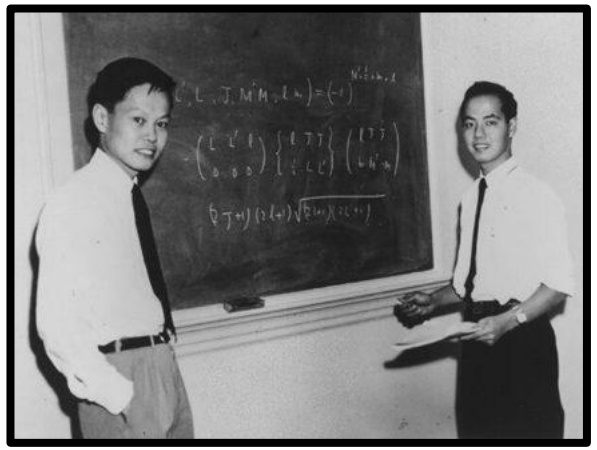


National Portrait Gallry

AND BROOKHAVEN

- The years 1950 to 1965 made C.N. Yang world-famous.
- His “favorites” parity nonconservation and Yang-Mills theory were from this period.
- Both were written while on leave at Brookhaven Lab.
- A series of seminal papers in the newly-developing particle physics, clarifying strong-weak force distinctions and in statistical physics. Many of these in collaboration with T.D. Lee.





TWO CULTURES

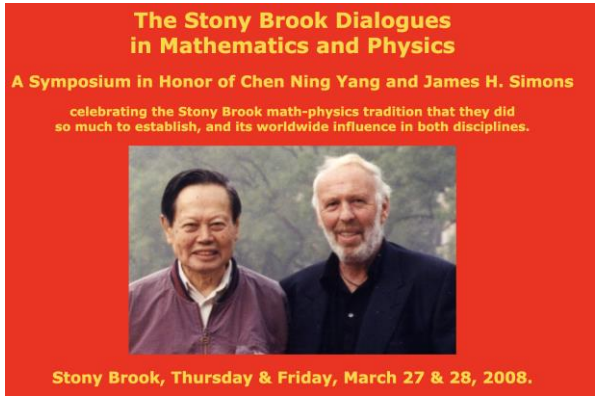
- As the first Chinese winners of the Nobel Prize, this honor had a special significance.
- "**I am in more than one sense a product of both the Chinese and Western cultures, in harmony and in conflict.**"
- As opportunities arose in the coming years, he made important efforts at reconciliation and collaboration.



Nobel Pize.org

THE STONY BROOK YEARS

- From 1966 – 1999, the longest single period of his career was as director of the Institute for Theoretical Physics at Stony Brook (now named for him).
- His steady leadership made the Institute a font of scientific advances, including supergravity, but not primarily by offering direction, but by being an example and recognizing excellence.
- **His interaction with mathematician Jim Simons provided a historic revival of mathematics-physics collaboration.**
- **Opened scientific and cultural roads between the U.S. and China. Advocated for fundamental science at the highest levels.**
- Recalling his own experience his guiding advice to many young scientists was that "It is better to enter a research area when it is new and developing."



YITP Stony Brook

- While teaching a class at Stony Brook, Femi's advice bore fruit -- Yang realized the close correspondence between the Riemann tensor and the Yang-Mills field strength.
- Gauge fields as geometric objects. Consistency requirements in gauge transformations in presence of monopoles.
- Conversations and then lectures by Simons on fiber bundles led to an influential paper of Yang with T.T. Wu, introducing a "dictionary" for the terminology of gauge fields and fiber bundles.
- A key step in the revitalization of mathematics-physics communication, echoing centuries past.

TABLE I. Translation of terminology.

Gauge field terminology	Bundle terminology
gauge (or global gauge)	principal coordinate bundle
gauge type	principal fiber bundle
gauge potential b^k_μ	connection on a principal fiber bundle
S_{ba} (see Sec. V)	transition function
phase factor Φ_{QP}	parallel displacement
field strength $f^k_{\mu\nu}$	curvature
source [a] J^k_μ	?
electromagnetism	connection on a $U_1(1)$ bundle
isotopic spin gauge field	connection on a SU_2 bundle
Dirac's monopole quantization	classification of $U_1(1)$ bundle according to first Chern class
electromagnetism without monopole	connection on a trivial $U_1(1)$ bundle
electromagnetism with monopole	connection on a nontrivial $U_1(1)$ bundle

[a] I.e., electric source. This is the generalization (see Ref. 3) of the concept of electric charges and currents.

T.T. Wu, C.N. Yang, Phys. Rev. D12, 3845 (1974)

CLOSING THE CIRCLE: RETURN TO TSINGHUA

- Frank Yang moved permanently to Tsinghua University in 2003, following death of Chi-Li Yang.
- Returned to Stony Brook for several extended visits with second wife, Fan Weng, including periods at the Simons Center for Geometry and Physics, an outgrowth of conversations thirty years earlier.
- Worked to develop and inspire research at Tsinghua, establishing another *Institute for Advanced Study.*
- In China, as a national figure, his preference & recommendations favored research with practical applications. This was not something new. He had expressed scepticism on prospects of a "final theory" as early as 1960.
- Many of his thoughts on the history of physics and on his predecessors can be found in his Selected Papers.
- He stayed in touch with friends until the closing months.

A UNIQUE LEGACY

- Frank Yang's legacy is with many of us every day, in what we're working on and in how we think about it. Most of all here at Stony Brook, where he spent 33 years.
- His influence is reflected in the growth of research in China.
- He himself did not follow us into all the new territories he helped discover. Perhaps there is an analogy here with Einstein and quantum mechanics.
- His appreciation of the beauty of mathematics was profound, but following Fermi, he preferred not to go too far from data. Remember, Yang-Mills was inspired by the proton and neutron.

C.N. Yang sought, until the end of his days, to recommend new directions

in which a young researcher could make an indelible mark,

as he himself did so many times.

This paper is "essential Yang" . . .

- **Grounded in reality**: at the start, experimental evidence for isospin symmetry is reviewed
- **Moves on to an utterly general question**: can proton-neutron symmetry be rephrased in epistemological terms? In a world with only strong interactions, p and n are different (fermions that can appear in the same state) but **distinguished only by definition.** Let *Y = (p,n); then . . .*

Gauge (group) transformation S "renames" the fermion y and vector boson fields B consistently, but leaves the action unchanged. Demand Locality – the 'name' depends on x.

$$\psi = S\psi', \quad B_\mu' = S^{-1}B_\mu S + \frac{i}{e}S^{-1}\frac{\partial S}{\partial x_\mu}.$$

- **Analogies are made to gauge invariance in electrodynamics and wave function phases in quantum mechanics, $S=e^{iq}$**, following in the footsteps of Weyl and Pauli.

- **The outcome is a simple proposal**, obviously incomplete at the time (**the symmetry seems to require vanishing masses for the vector B**), but of astounding generality, far beyond that of its original inspiration.
- **An aside: for Yang, SU(2)'s connection with quaternion**s suggested a special status for this group, perhaps as the "phase" of a generalized quantum mechanics (Yang & Lee 1958). It was not to be, but it illustrates the seriousness of the proposal.

- Yang described Fermi's lessons for young researchers just starting out as: "devote most of one's time to attacking simple practical problems rather than deep fundamental ones."
- Still, for an alternate perspective of what his student days were like, a quote from James Cronin in Frank's birthday volume "It was clear that Frank . .. . was so talented in theoretical physics that it made no sense to continue his experimental studies."
- Frank wrote that the groundwork for his own great advances was laid at Chicago in his study of four areas based on then-recent intellectual advances,

1. Onsager on the Ising Model
2. Bethe on spin waves
3. Pauli on QFT
4. "Many papers" on angular distribution in nuclear reactions

For a sense of exciting times in the still-new particle physics, I recommend as an example . . .

"**Theoretical Discussion on Possible High energy neutrino experiments**"

T.D. Lee & C.N. Yang *Phys. Rev. Lett.* 4, 6 (1960)

right after a paper by Melvin Schwartz proposing high energy neutrino beams.

All at once, it would be possible to test . . .

- One or two types of neutrinos, "conservation of leptons", lepton universality
- The point structure of currents and the relevance of inclusive cross sections (anticipating deep inelastic electron-proton scattering ten years later)
- The Feynman-Gell-Mann "CVC" hypothesis
- Proposals for a "weakly coupled boson" (named "W" here), neutral currents and the implications of unitarity

All this in one 4 ½ page paper!