Now it looks so easy …
(A History of the "Higgs Mechanism")

49th SLAC Summer Institute · 23 August 2021

"Electroweak Symmetry Breaking in Historical Perspective," Ann. Rev. Nucl. Part. Sci. 65, 25 (2015)

A word about my (assigned) title … from Peter Higgs

Contrary to the custom at this conference, I want first of all to disclaim priority for some of the concepts to which my name is commonly attached in the literature. For this exaggerated view of my originality I have to thank the late Ben Lee, who at the 1972 High Energy Physics Conference at Fermilab plastered my name over almost everything concerned with spontaneous symmetry breaking. "Higgs fields", for example, are just the scalar fields of a linear sigma model, which was discussed in 1960 by Gell-Mann and Lévy[1] but had been introduced three years earlier by Schwinger[2]. And "the Higgs mechanism" was first described by Philip Anderson[3]: perhaps it should be called "the ABEGHHK'tH.... mechanism" after all the people (Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble, 't Hooft) who have discovered or rediscovered it! However, I do accept responsibility for the Higgs boson; I believe that I was the first to draw attention to its existence in spontaneously broken gauge theories[4].


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In their own words …

Several of the leading actors in the discovery of spontaneous gauge symmetry breaking as an origin of particle mass have described their personal involvement. Their words carry a special fascination.

Interview with **Philip Anderson** by Alexei Kojevnikov, November 23, 1999, Niels Bohr Library & Archives, American Institute of Physics: passage beginning "Now, during that year in Cambridge …"

Franck Daninos's interview with **François Englert** : « Le LHC détectera le boson de Higgs … s'il existe » ("The LHC will detect the Higgs boson … if it exists"), *La Recherche* **419**, 58 (May 2008).
F. Englert, "Broken Symmetry and Yang–Mills Theory," in *50 Years of Yang–Mills Theories,* ed. G. 't Hooft, World Scientific, Singapore, 2005, p. 65; "The BEH Mechanism and Its Scalar Boson," 2013 Nobel Lecture.

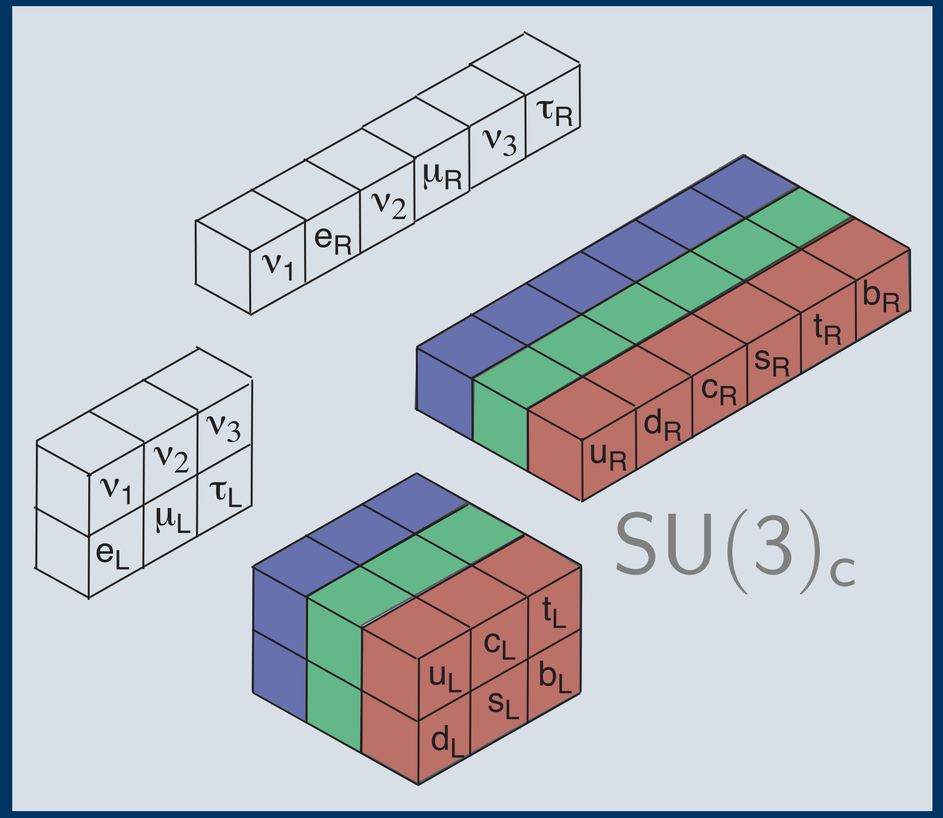
G. S. Guralnik, "The History of the Guralnik, Hagen and Kibble Development of the Theory of Spontaneous Symmetry Breaking and Gauge Particles," *Int. J. Mod. Phys.* **24**, 2601 (2009); "Gauge Invariance and the Goldstone Theorem," *Mod. Phys. Lett. A* **26**, 1381 (2011); "Heretical Ideas that Provided the Cornerstone for the Standard Model of Particle Physics," Swiss Physical Society *Milestones in Physics* (May 2013); with **C. R. Hagen**, "Where Have All the Goldstone Bosons Gone?" arXiv:1401.6924.

P. W. Higgs, "SBGT and all that," in *Discovery of Weak Neutral Currents: The Weak Interaction Before and After,* ed. A. K. Mann and D. B. Cline, AIP Conf. Proc. 300, 159 (1994); "My Life as a Boson: The Story of 'The Higgs'," *Int. J. Mod. Phys. A* **17S1**, 86 (2002); "Evading the Goldstone Theorem," 2013 Nobel Lecture.

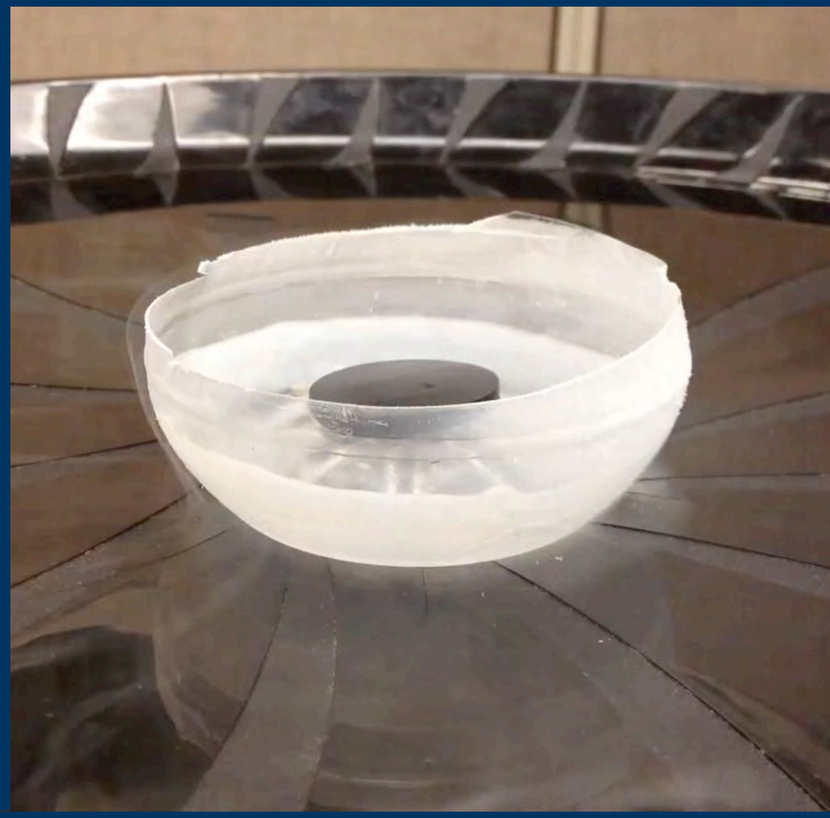
T. W. B. Kibble, "Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism (History)," *Scholarpedia* **4**(1), 8741 (2009); "It didn't seem that special at the time," interview by Alok Jha, *The Observer,* Saturday 10 August 2013.

2010 J. J. Sakurai Prize for Theoretical Particle Physics videos on YouTube.

Chiral quarks and leptons + gauge symmetry + Meissner effect



$$\cancel{SU(2)_L \otimes U(1)_Y} \rightarrow U(1)_{EM}$$



Ca. 1960: *p n e μ*

Neutrino detected in inverse β-decay.

Charged-current weak interaction is left-handed.

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + \beta + \bar{\nu}$$

and $\pi \rightarrow \mu \rightarrow e$ chain

ν is left-handed

V–A extension of Fermi β-decay theory ruled … as an effective theory, but σ rises with energy, suggesting the need for a massive force carrier.

Apparent universal strength of β-decay, μ-decay.

Similarity of EM, weak matrix elements: CVC.

For theorists: example of the Yang–Mills construction.

Partial conservation, e.g., PCAC: $\partial_\mu A^\mu \propto$ pion field

8.B

Nuclear Physics **22** (1961) 579—588; © *North-Holland Publishing Co., Amsterdam*

$$\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW †

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 9 September 1960

Abstract: Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are introduced. Since the latter possibility yields a theory disagreeing with experiment, the simplest partially-symmetric model reproducing the observed electromagnetic and weak interactions of leptons requires the existence of at least four vector-boson fields (including the photon). Corresponding partially-conserved quantities suggest leptonic analogues to the conserved quantities associated with strong interactions: strangeness and isobaric spin.

1. Introduction

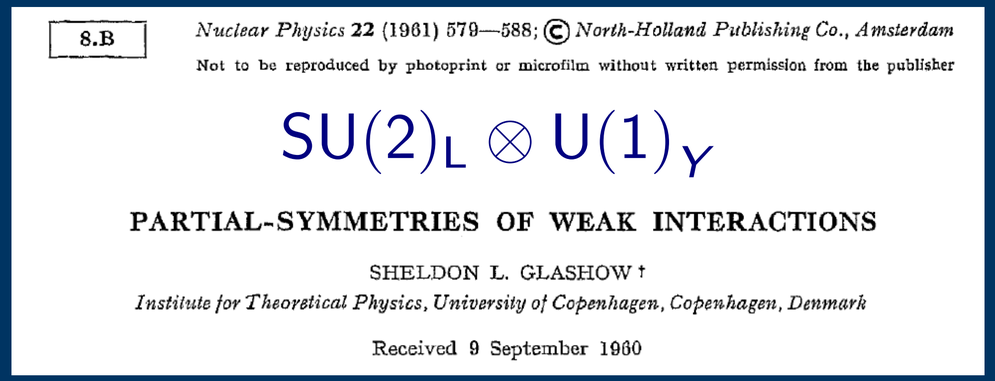
At first sight there may be little or no similarity between electromagnetic effects and the phenomena associated with weak interactions. Yet certain remarkable parallels emerge with the supposition that the weak interactions are mediated by unstable bosons. Both interactions are universal, for only a single coupling constant suffices to describe a wide class of phenomena: both interactions are generated by vectorial Yukawa couplings of spin-one fields ††. Schwinger first suggested the existence of an "isotopic" triplet of vector fields whose universal couplings would generate both the weak interactions and electromagnetism — the two oppositely charged fields mediate weak interactions and the neutral field is light [2]). A certain ambiguity beclouds the self-interactions among the three vector bosons; these can equivalently be interpreted as weak or electromagnetic couplings. The more recent accumulation of experimental evidence supporting the $\Delta I = \frac{1}{2}$ rule characterizing the non-leptonic decay modes of strange particles indicates a need for at least one additional neutral intermediary [3]).

The mass of the charged intermediaries must be greater than the K-meson mass, but the photon mass is zero — surely this is the principal stumbling block in any pursuit of the analogy between hypothetical vector mesons and photons. It is a stumbling block we must overlook. To say that the decay intermediaries

† National Science Foundation Post-Doctoral Fellow. Present Address: Physics Department, California Institute of Technology, Pasadena.

†† A scalar intermediary is also conceivable. See ref. [1]).

Sheldon Glashow



8.B

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$$SU(2)_L \otimes U(1)_Y$$

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SHELDON L. GLASHOW †

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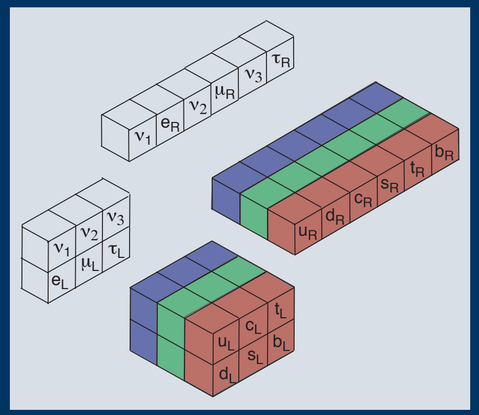
Received 9 September 1960

Weak hypercharge: $Q = I_3 + \frac{1}{2}Y \quad Y_L = -1,\ Y_R = -2$

I_3 and Y gauge bosons mix: θ_W
Weak neutral current and EM result.

Massless photon by decree;
no prediction for intermediate boson masses.

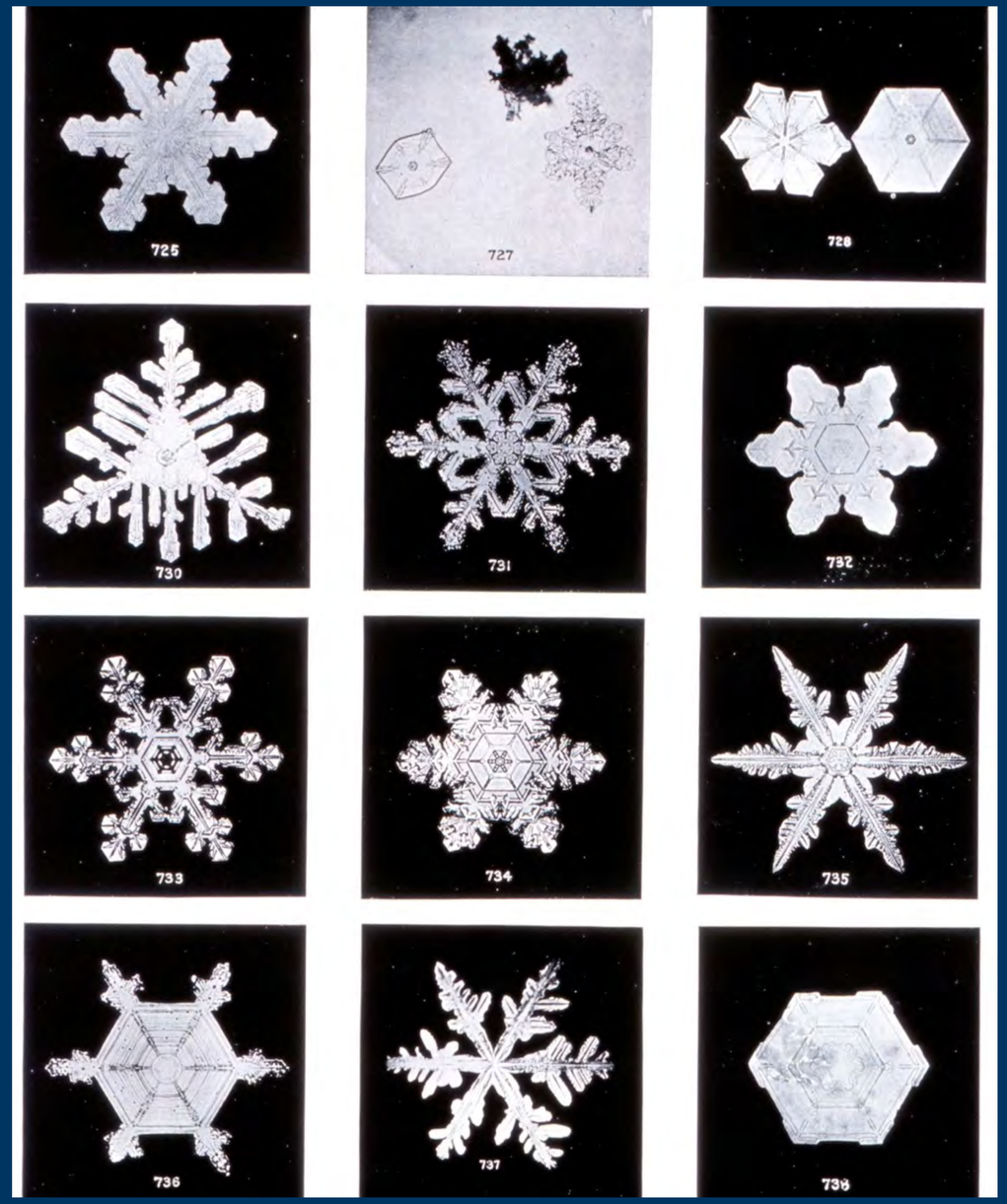


Lepton masses assumed, not discussed.

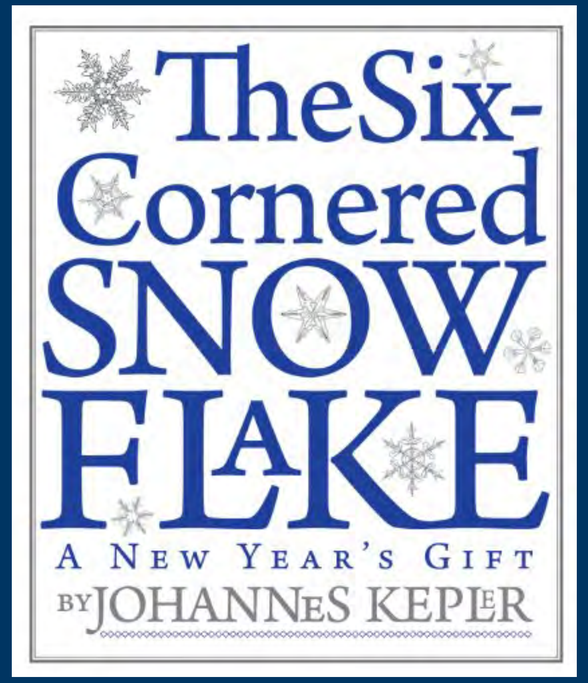
$$\bar{e}e = \frac{1}{2}\bar{e}(1-\gamma_5)e + \frac{1}{2}\bar{e}(1+\gamma_5)e = \bar{e}_R e_L + \bar{e}_L e_R$$

Secret symmetry #1: the six-cornered snowflake

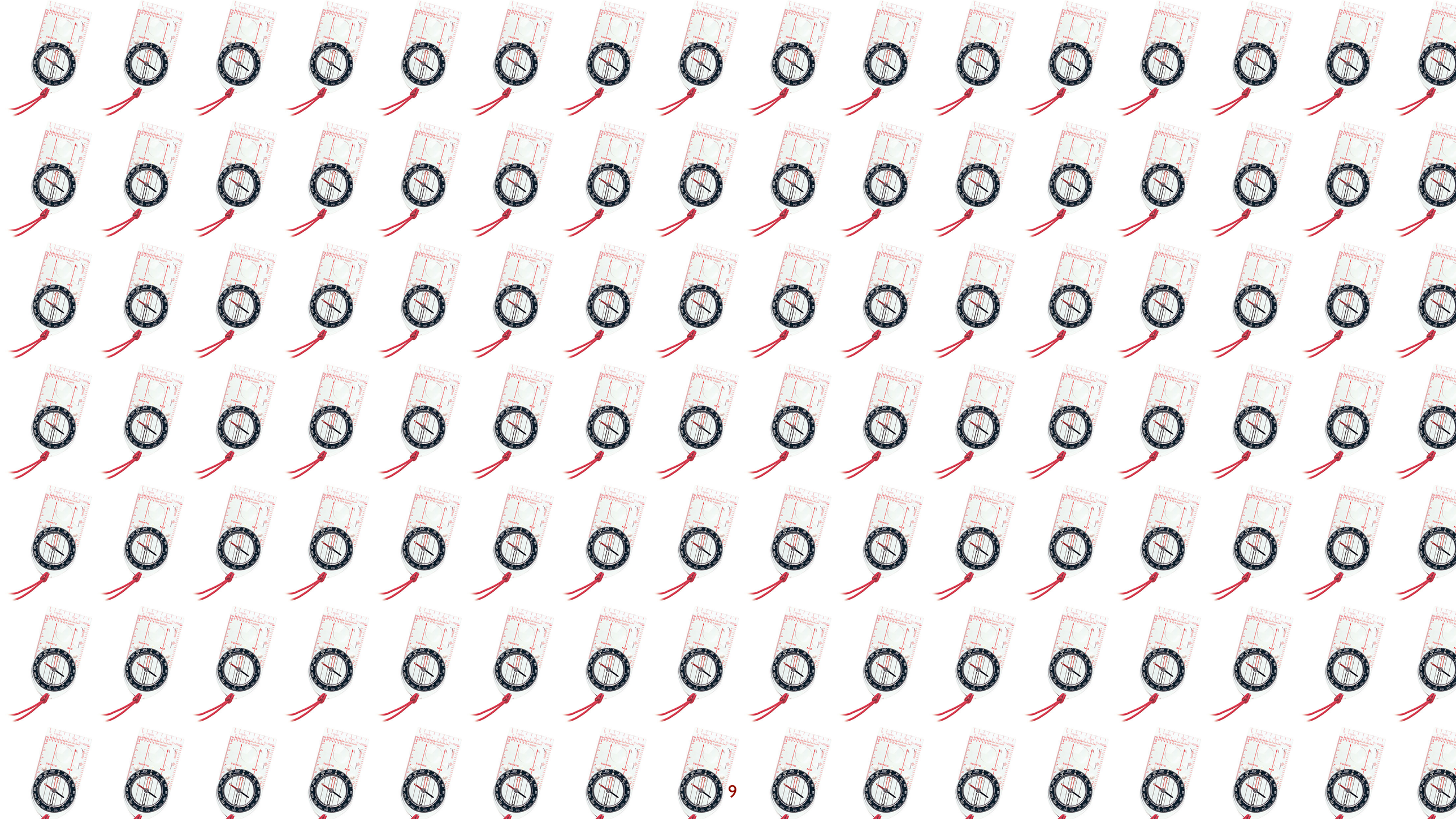
Johannes Kepler (1571–1630)



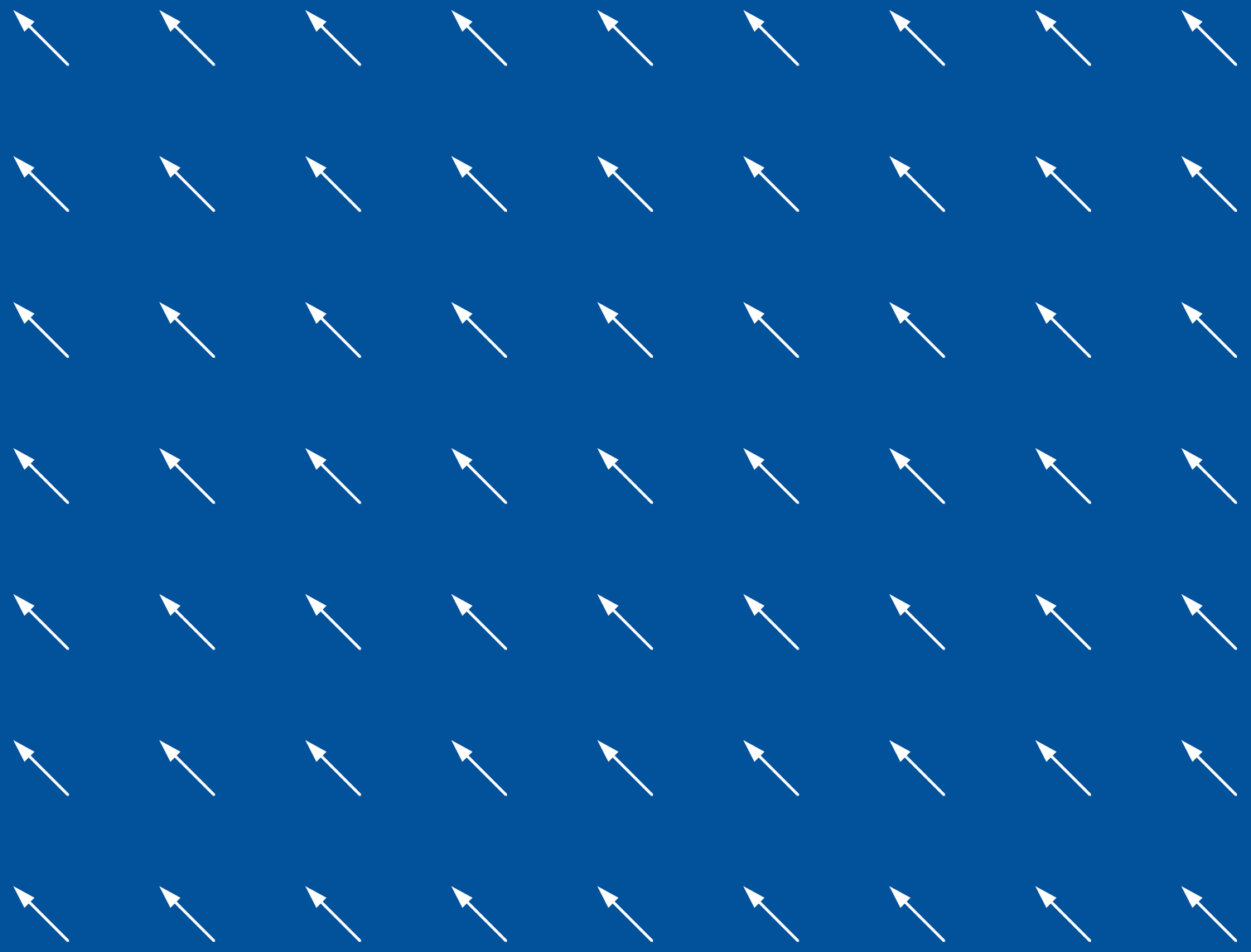
Studies among the Snow Crystals ... by Wilson Bentley, via NOAA Photo Library



Water drop : disorder : O(3)
Snowflake : order : D_6



The Picophysicist's Tale



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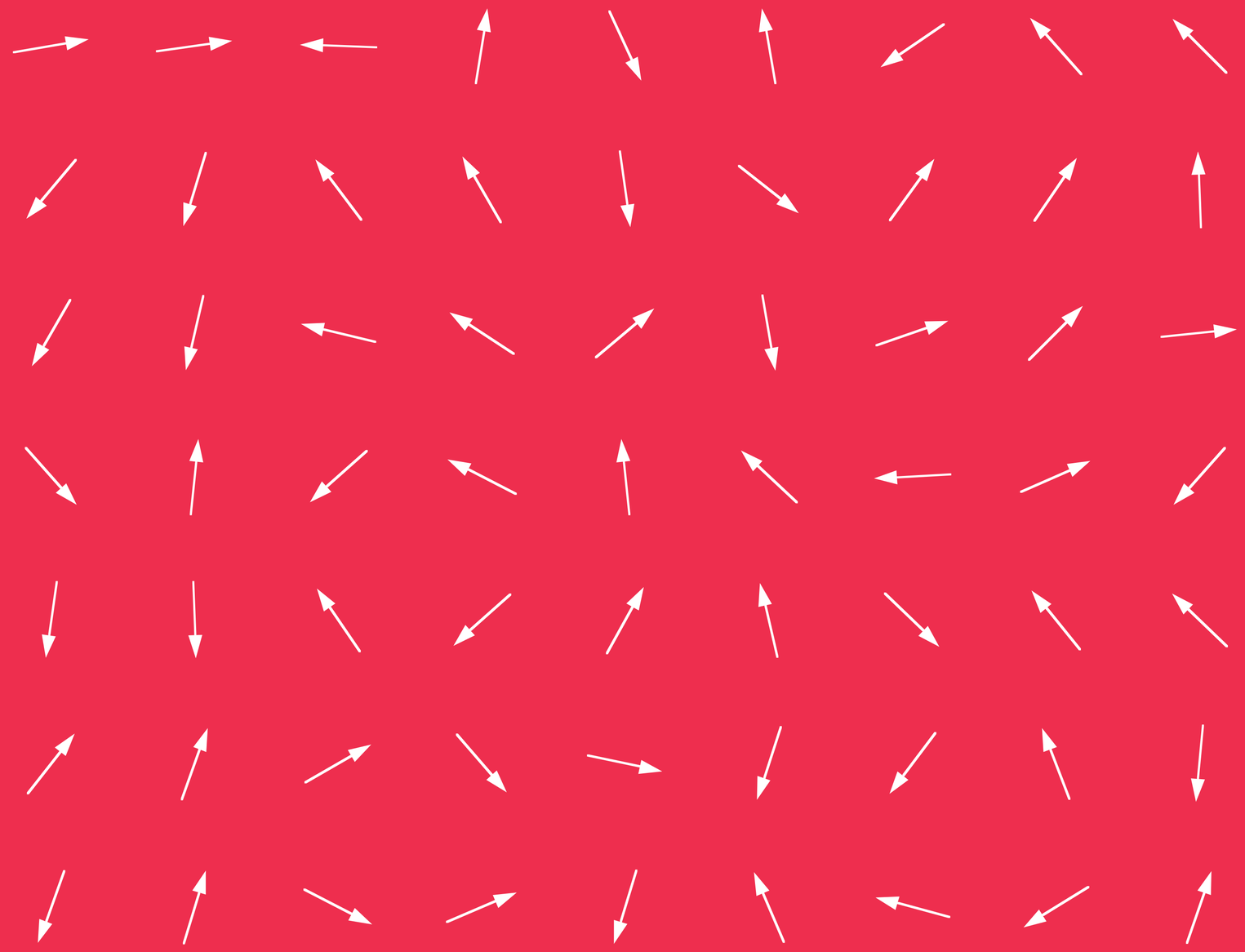

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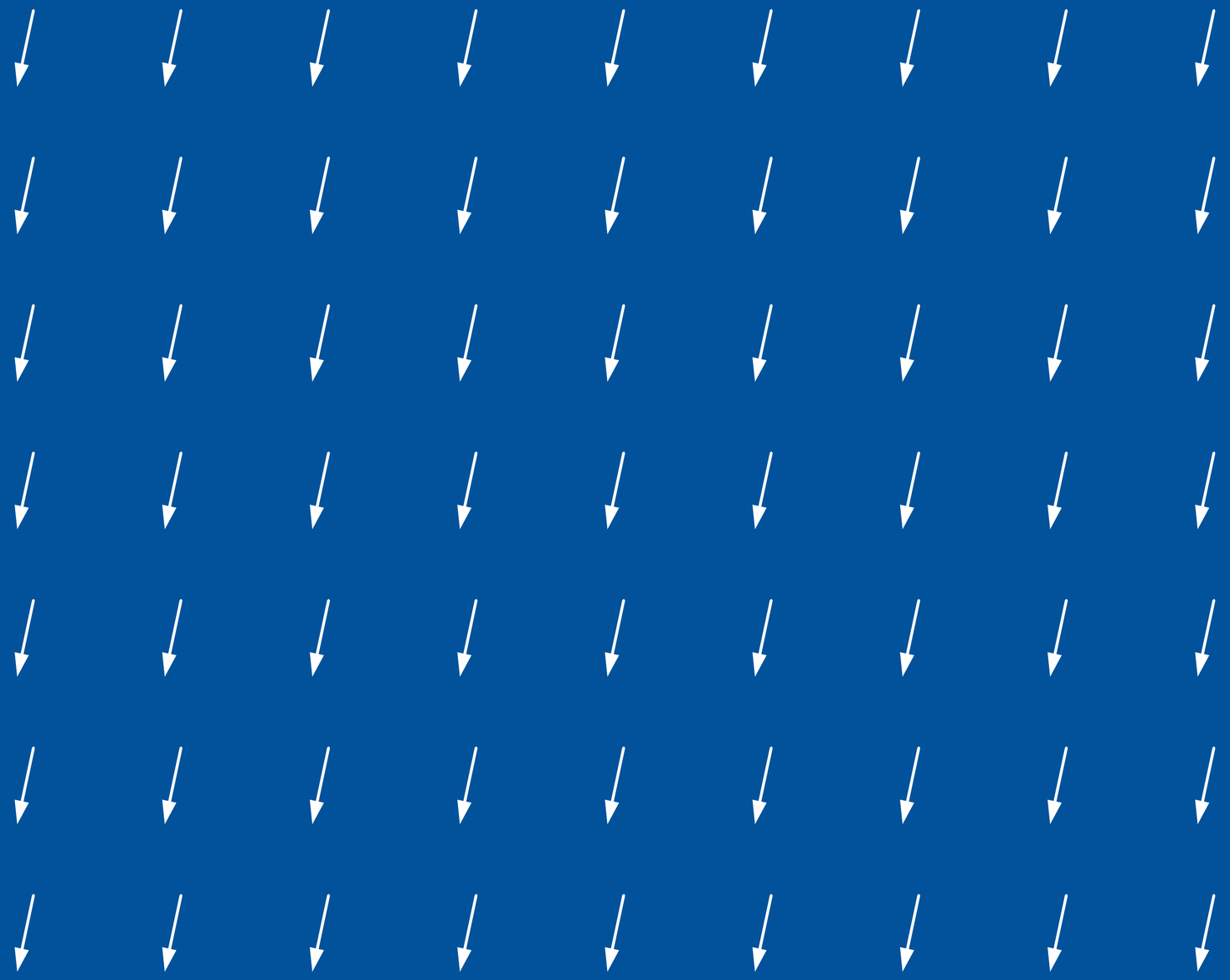
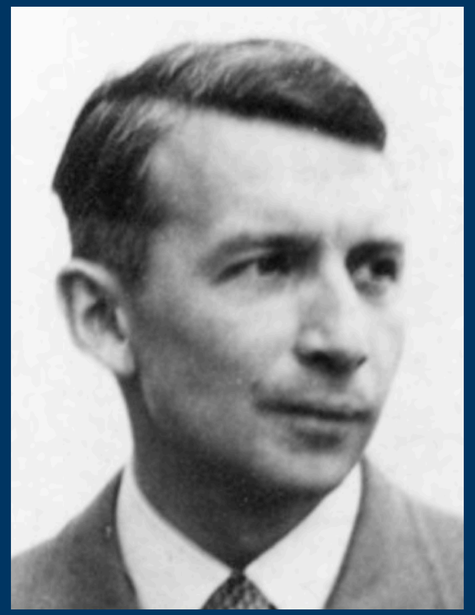
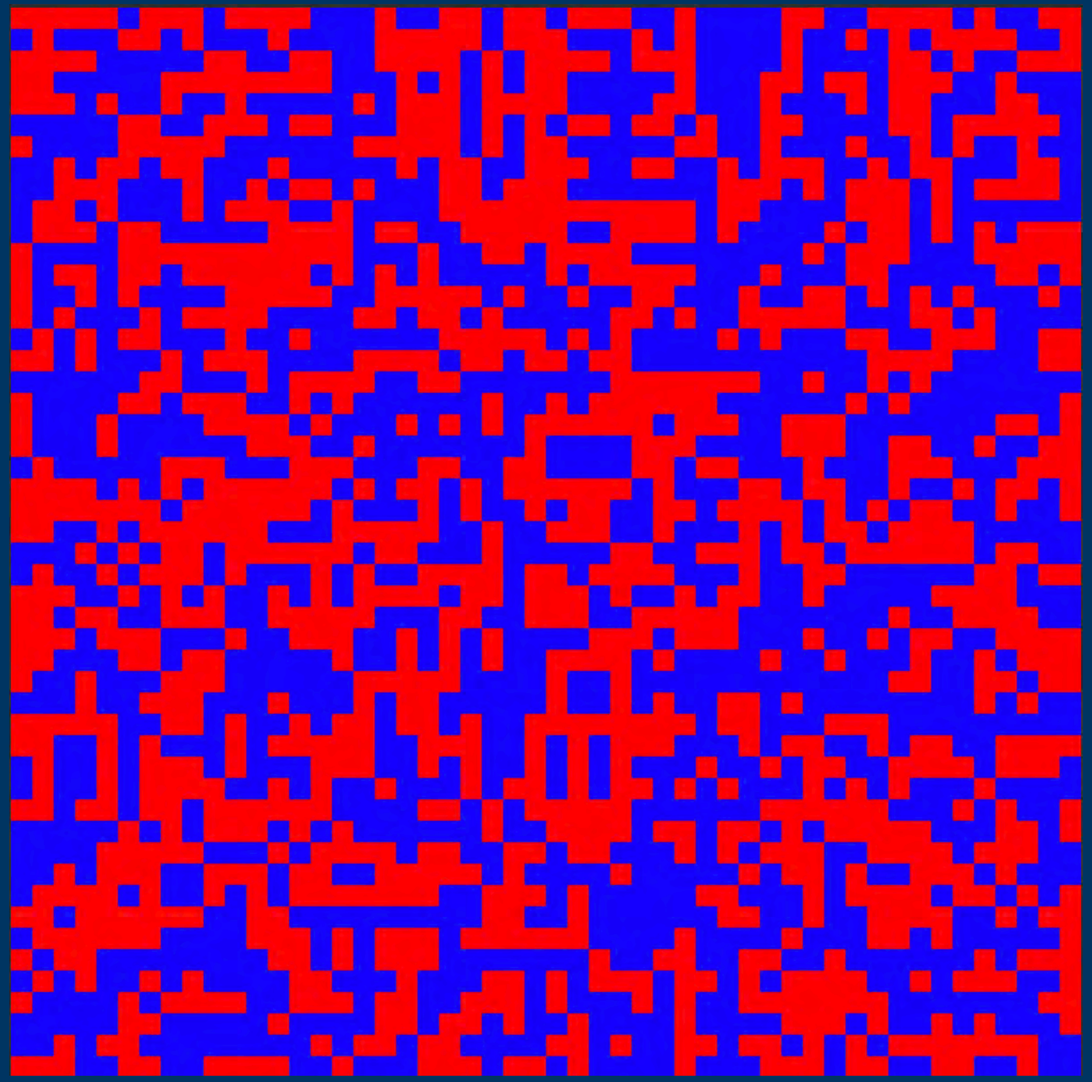


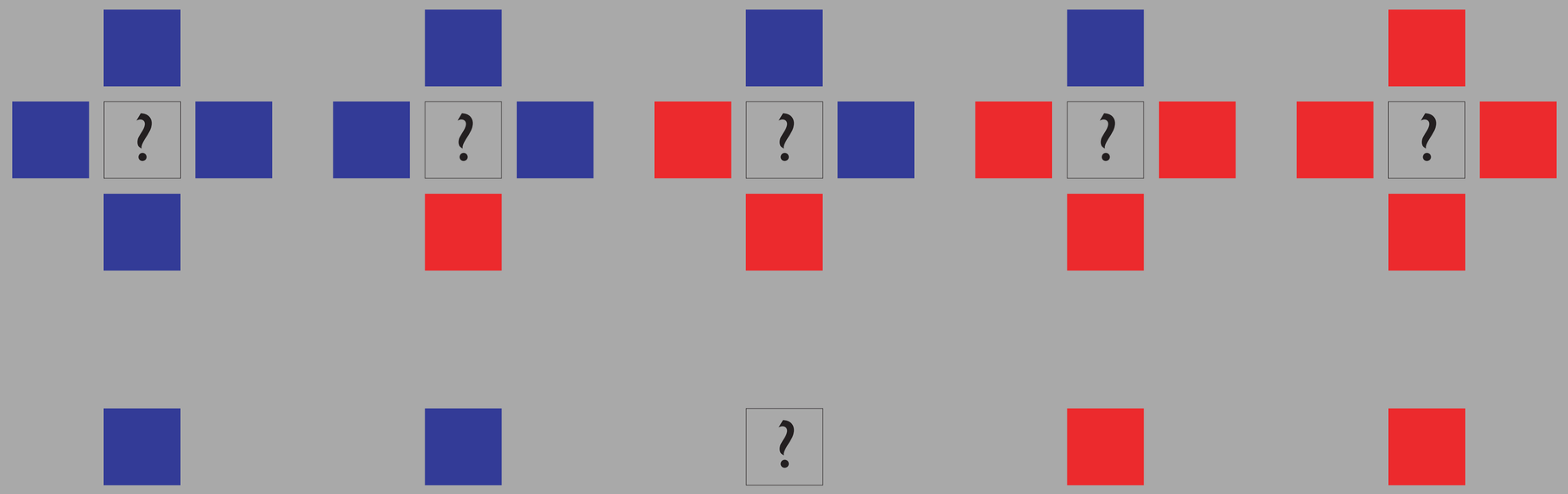
Secret symmetry #2: spontaneous magnetization



Ernst Ising (1900–1998)



Rules of the game (plus thermal agitation)

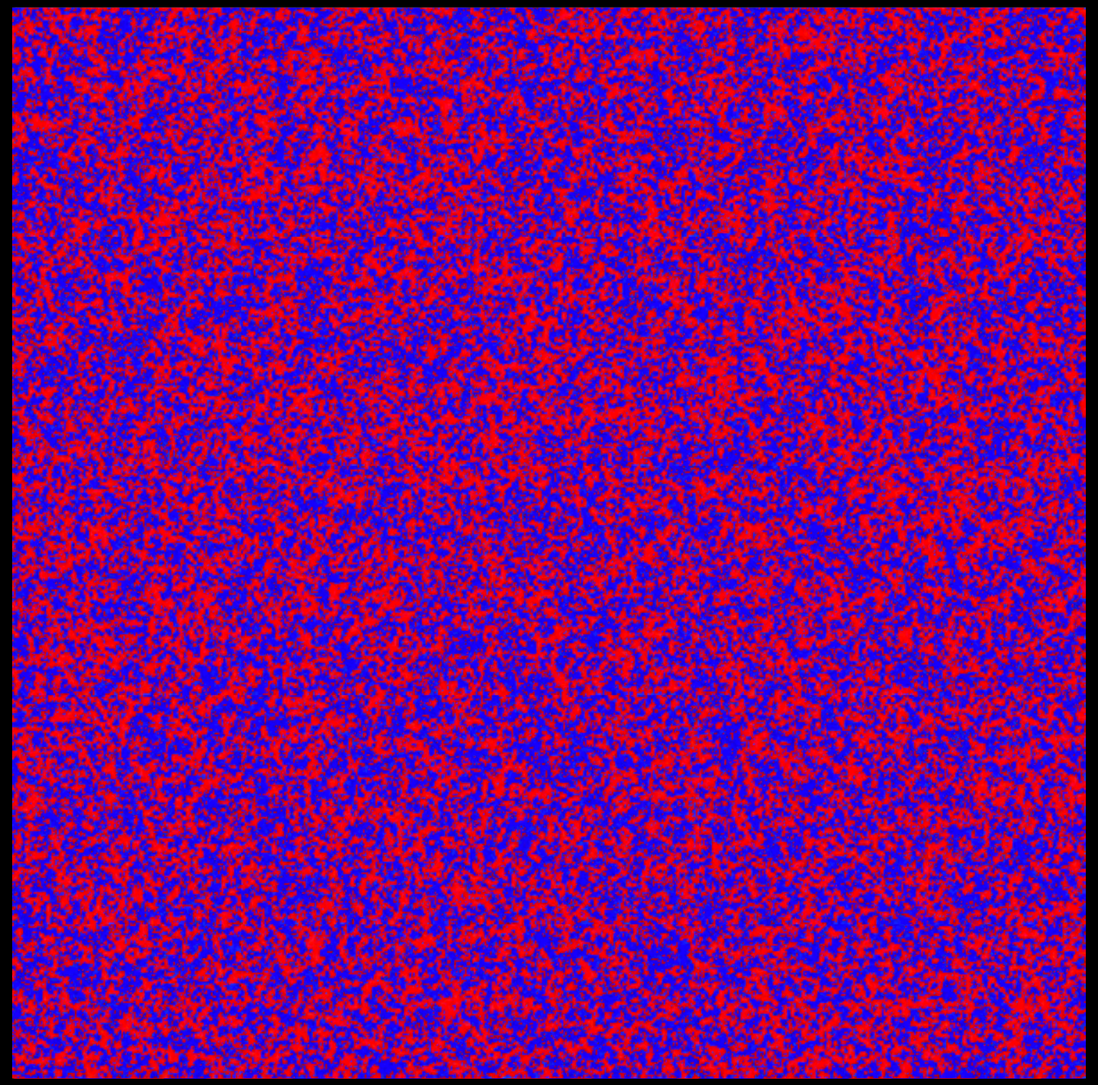



LARS ONSAGER
1903 - 1976


NTH

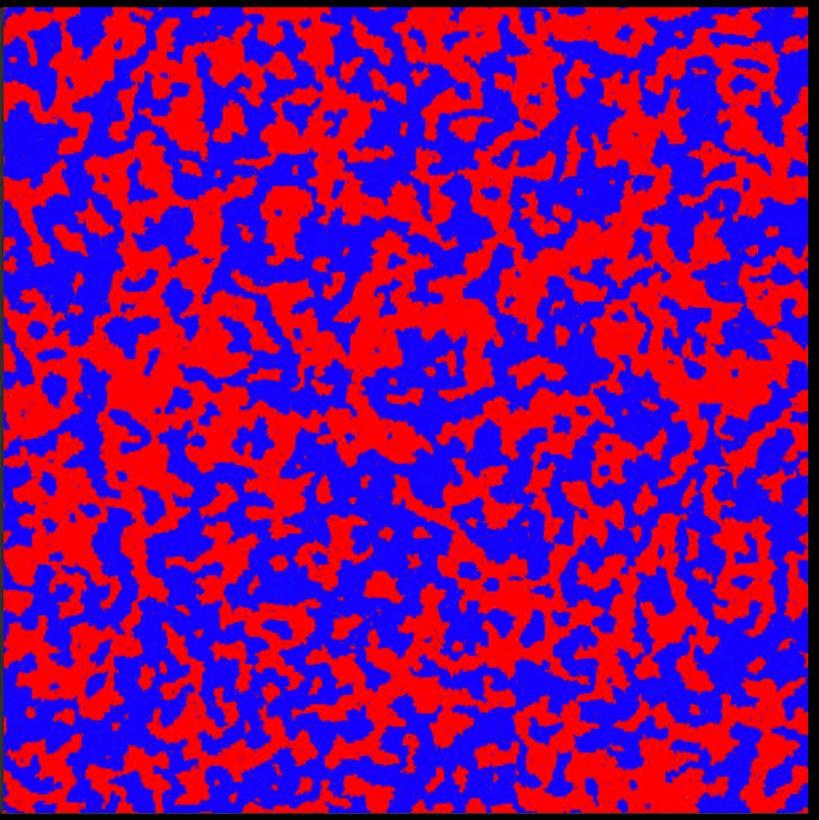
Secret symmetry #2: spontaneous magnetization

Ernst Ising (1900–1998)

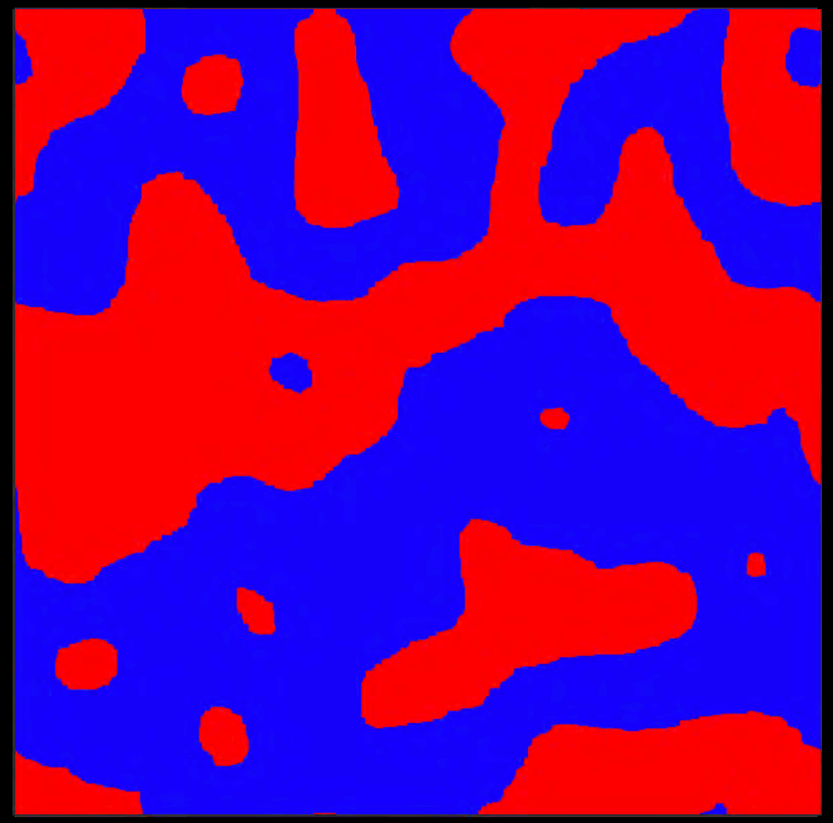


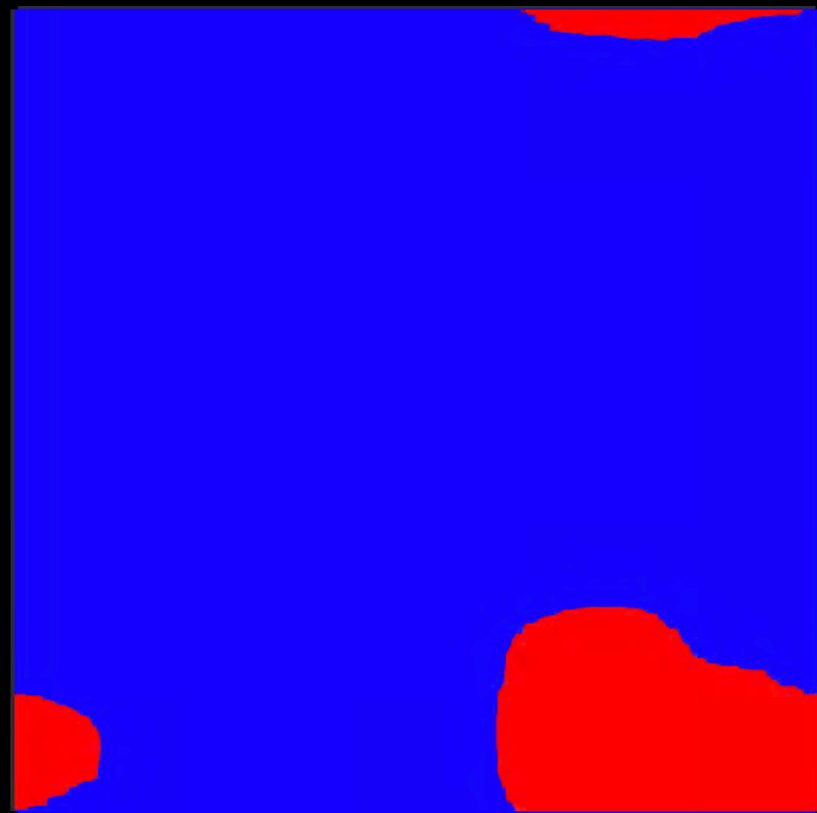
Lars Onsager (1903–1976)

Cool below critical temperature $T_c = \frac{2}{\ln(1+\sqrt{2})} \approx 2.269$



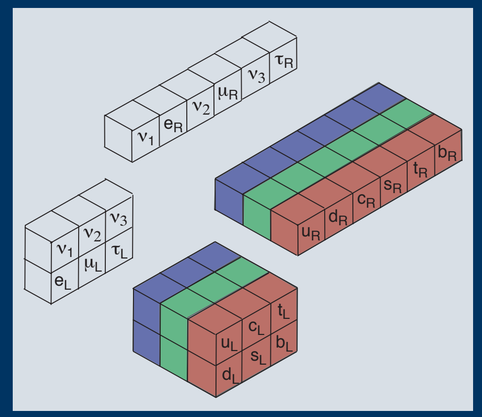
Dan Schroeder simulation (download!)





Symmetric laws *need not imply* symmetric outcomes.

Parity violation in charged-current weak interactions

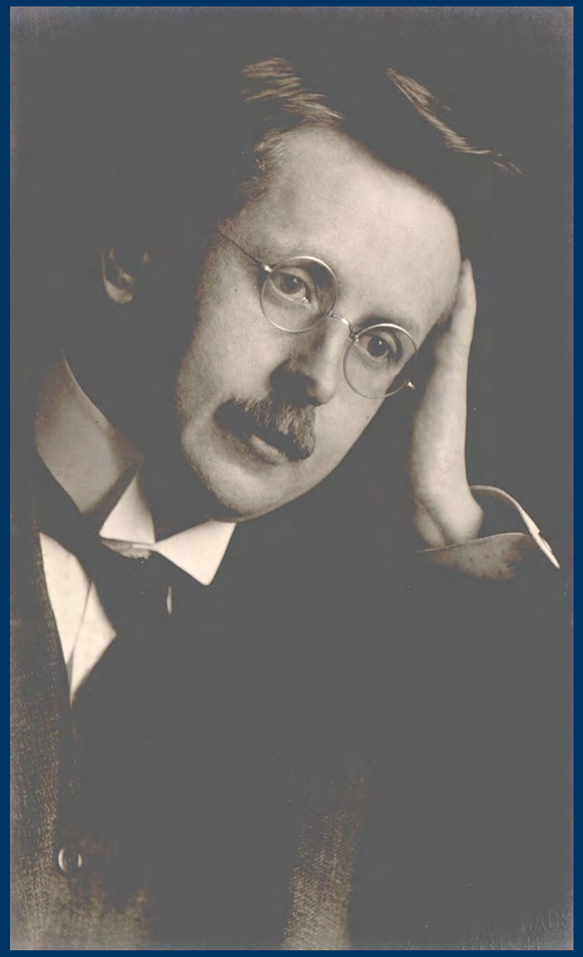



Es ist uns eine traurige Pflicht,
bekannt zu geben, daß unsere
langjährige, liebe Freundin
PARITY
am 19. Januar 1957 nach kurzem
Leiden bei weiteren experimentellen
Eingriffen sanft entschlafen ist
Für die Hinterbliebenen
e, μ, ν.

Pauli to Weisskopf:
It is our sad duty to announce that
our loyal friend of many years
PARITY
went peacefully to her eternal rest on
the nineteenth of January 1957, after
a short period of suffering in the face
of further experimental interventions.
For those who survive her,
e, μ, ν.

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_Y \ ?$$

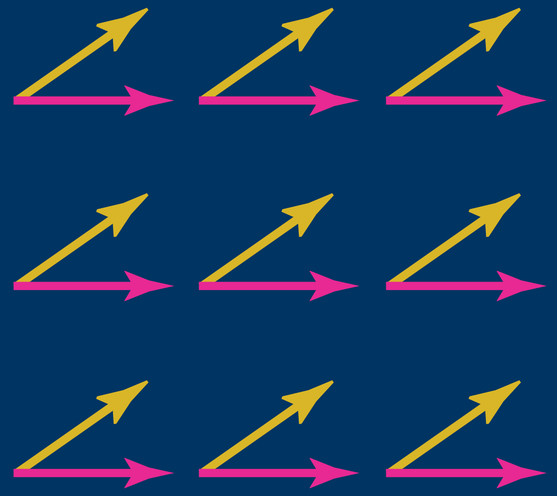
Can symmetries dictate interactions?



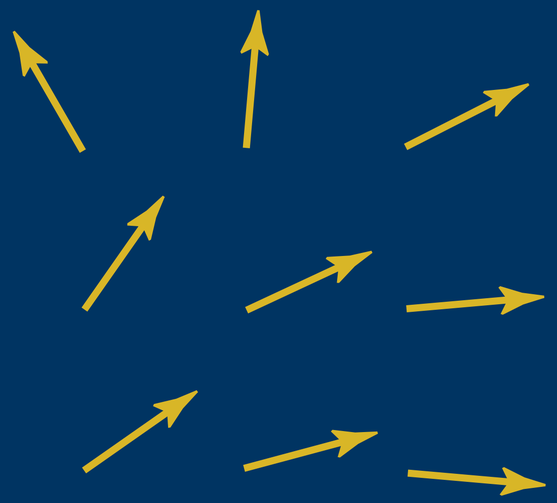
Hermann Weyl (1918, 1929)

Local phase invariance $\Longrightarrow$ *QED*

Complex phase in QM



Global: free particle



Local: interactions

Can symmetries dictate interactions?

Emmy Noether (1918)

CQ, "A Century of Noether's Theorem," essay | slides

Noether's Second Theorem $\Longrightarrow$ *Yes!*

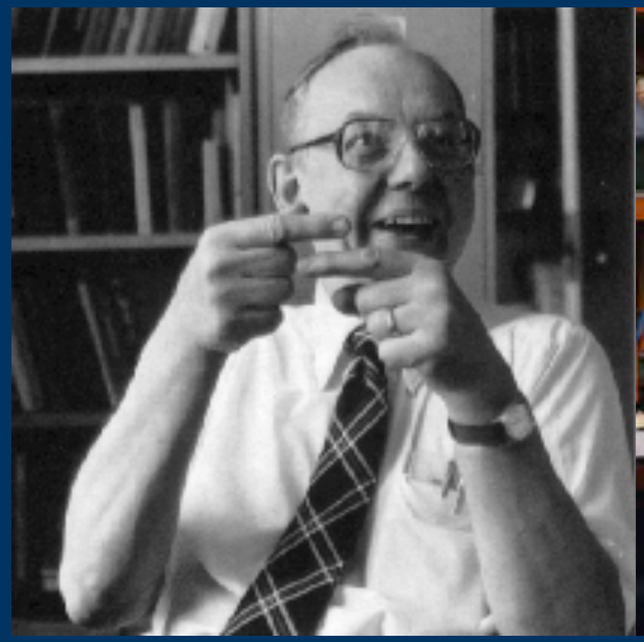
Symmetry matters: conservation laws

Translation in space No preferred location	$\Leftrightarrow$	Momentum Conservation
Translation in time No preferred time	$\Leftrightarrow$	Energy Conservation
Rotational invariance No preferred direction	$\Leftrightarrow$	Angular Momentum Conservation

All special cases of Noether's First Theorem for continuous symmetries

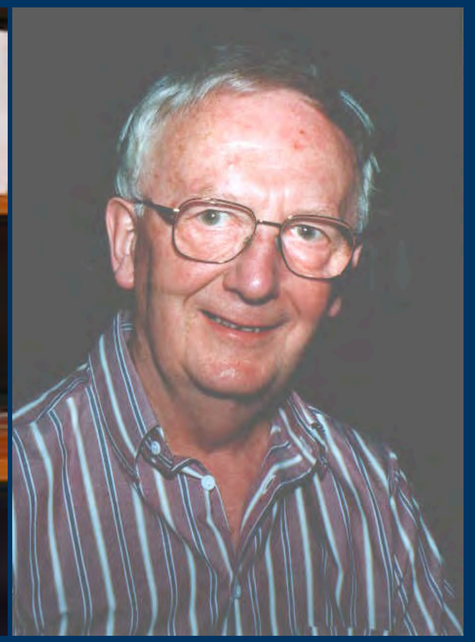
Second Theorem: maximum generalization in group theory of "general relativity"

First application to an internal symmetry (isospin)



Robert Mills

C.N.Yang



Ron Shaw

(1954)

Massless vector isovector mediators of nuclear forces

(Not in this world!)

In GR, 3-index Christoffel symbols take the role of gauge fields.

Absent EM, labels of *p* and *n* are arbitrary

Designate locally?

Yes, if introduce an adjoint representation of spin-1 gauge bosons, naturally massless.

Nucleon mass allowed (not explained), because L and R transform identically.

Free nucleon Lagrangian

$$\mathcal{L} = \bar{p}(i\gamma^\mu\partial_\mu - m)p + \bar{n}(i\gamma^\mu\partial_\mu - m)n.$$

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi. \quad \psi \equiv \begin{pmatrix} p \\ n \end{pmatrix}$$

Global isospin: $\psi \to \exp\left(\frac{i\boldsymbol{\alpha}\cdot\boldsymbol{\tau}}{2}\right)\psi$

Yang–Mills Theory

Local isospin: $\boldsymbol{\alpha} \to \boldsymbol{\alpha}(x)$

$$\mathcal{D}_\mu \equiv I\partial_\mu + igB_\mu$$

$$B_\mu = \tfrac{1}{2}\boldsymbol{\tau}\cdot\mathbf{b}_\mu = \tfrac{1}{2}\tau^a b^a_\mu = \tfrac{1}{2}\begin{pmatrix} b^3_\mu & b^1_\mu - ib^2_\mu \\ b^1_\mu + ib^2_\mu & -b^3_\mu \end{pmatrix}$$

$$b'^l_\mu = b^l_\mu - \varepsilon_{jkl}\alpha^j b^k - \frac{1}{g}\partial_\mu\alpha^l$$

$$F_{\mu\nu} = \frac{1}{ig}\left[\mathcal{D}_\nu, \mathcal{D}_\mu\right] = \partial_\nu B_\mu - \partial_\mu B_\nu + ig\left[B_\nu, B_\mu\right]$$

$$F^l_{\mu\nu} = \partial_\nu b^l_\mu - \partial_\mu b^l_\nu + g\varepsilon_{jkl}b^j_\mu b^k_\nu$$

$$\mathcal{L}_{\mathrm{YM}} = \bar{\psi}(i\gamma^\mu\mathcal{D}_\mu - m)\psi - \tfrac{1}{2}\mathrm{tr}\left(F_{\mu\nu}F^{\mu\nu}\right)$$

$M^2 B_\mu B^\mu$ breaks gauge invariance

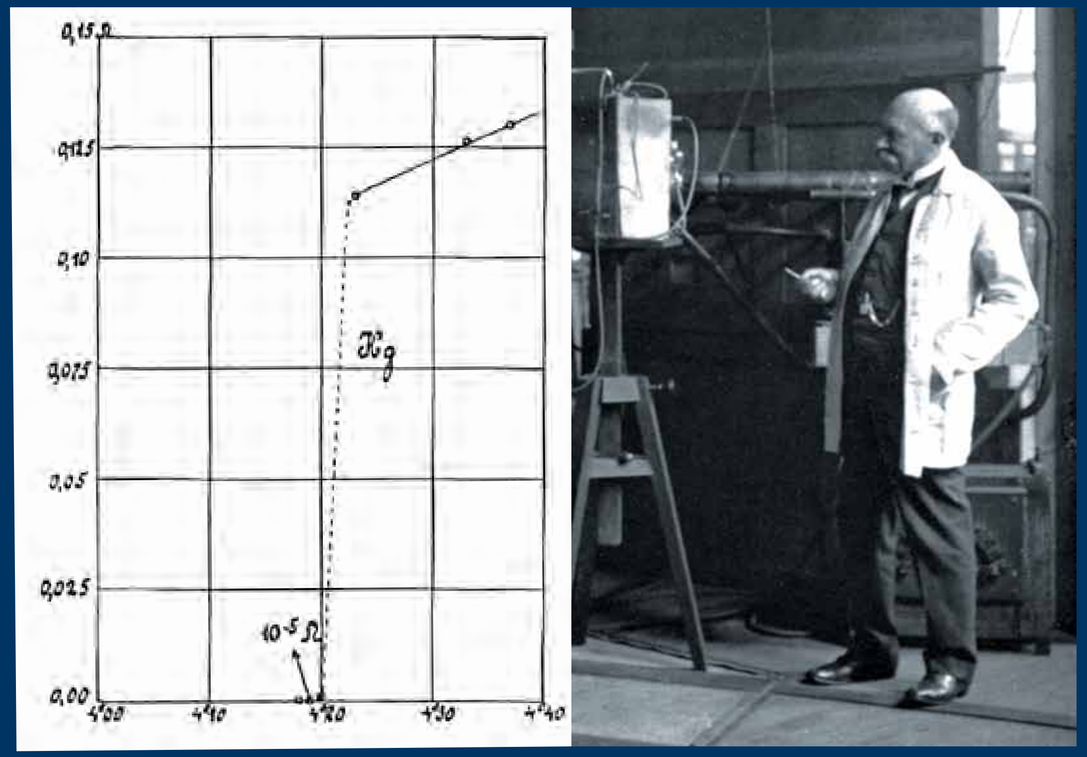
Two decades later: $SU(2)_I \Rightarrow SU(3)_c \longrightarrow$ QCD

In contrast to biological evolution, unsuccessful lines in theoretical physics do not become extinguished, never to rise again.

We are free to borrow potent ideas from the past and to apply them in new settings, often to powerful effect.

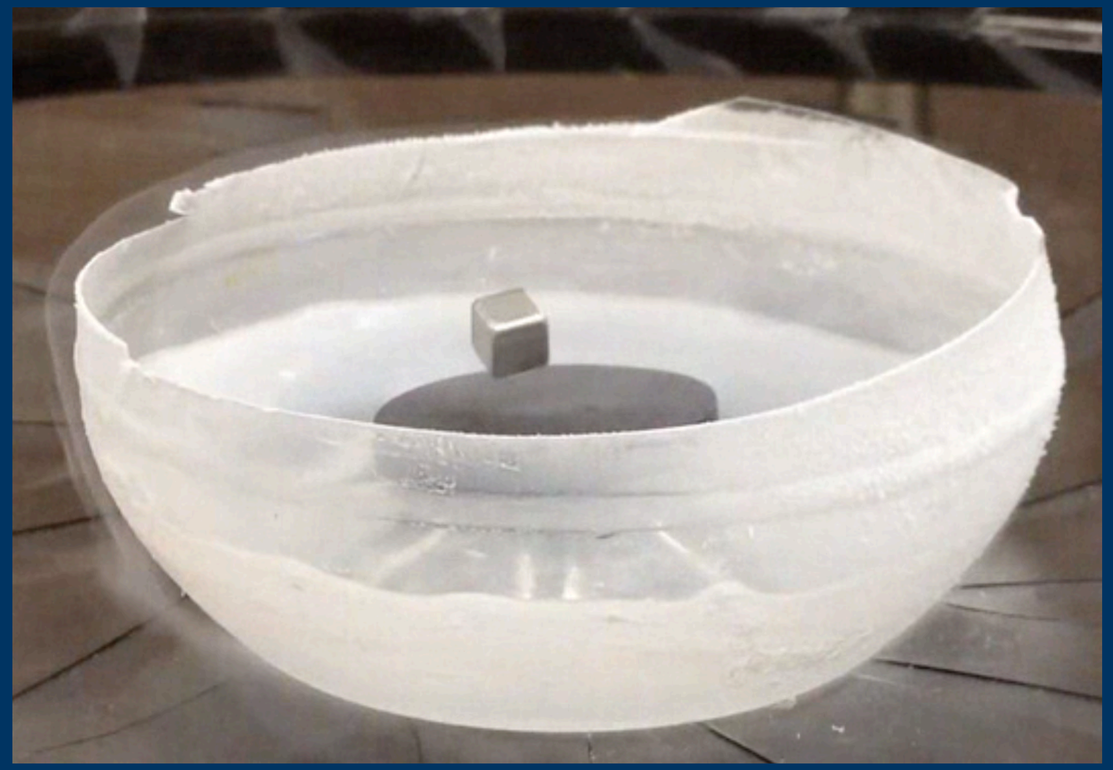
How to endow the gauge bosons with mass?
A hint from superconductivity …

Miracle #1



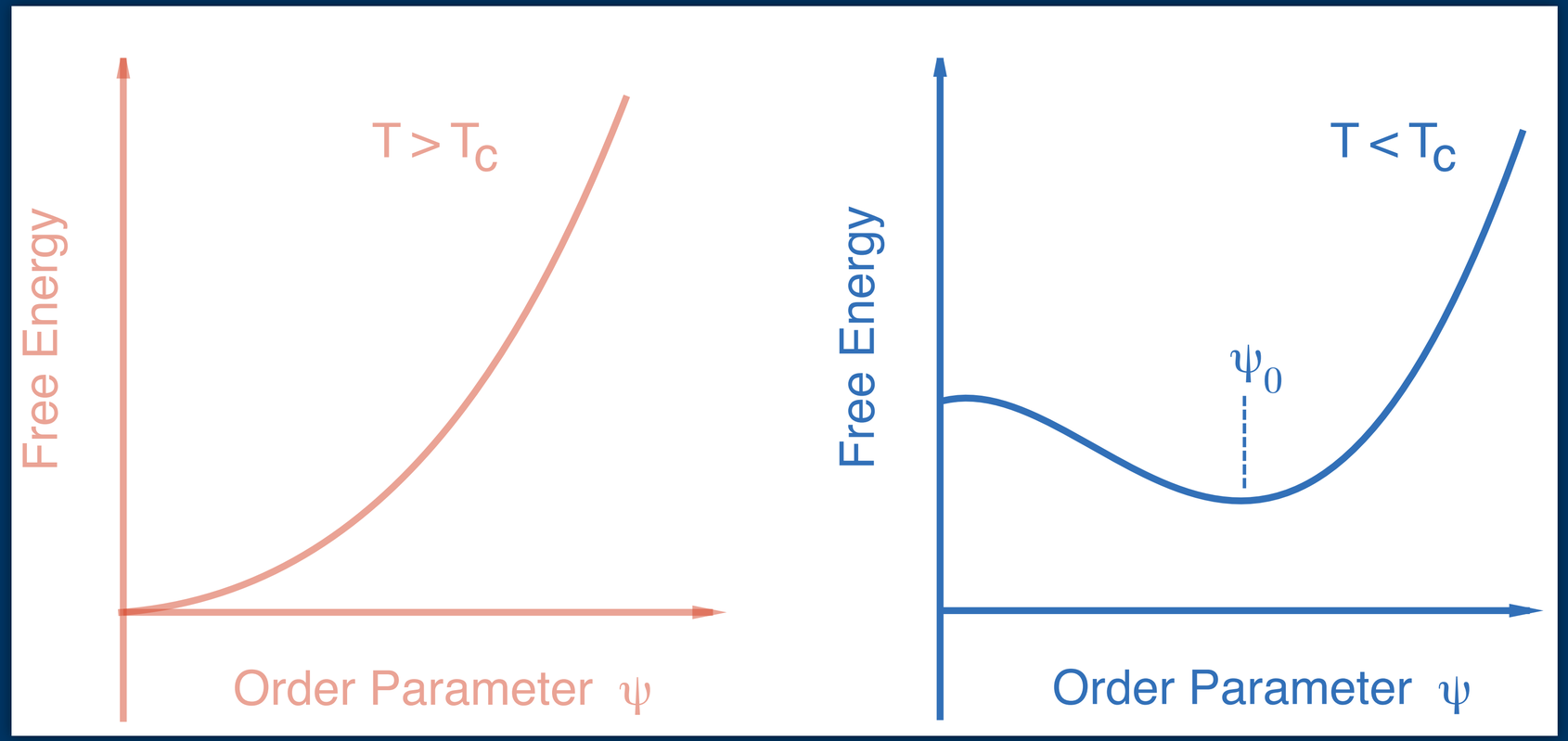
Heike Kamerlingh Onnes (1911)

Miracle #2



Meissner & Ochsenfeld (1933)

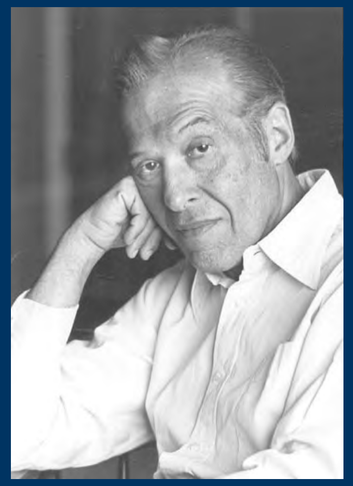
Ginzburg–Landau description (1950)



Photon acquires mass in superconductor; $U(1)_{EM} \rightarrow C_2$, phase rotations by π

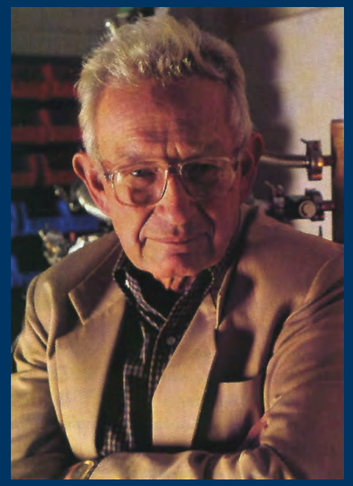
Later: Abelian Higgs model

Hints that massive gauge bosons might be possible …



Julian Schwinger

(1962) Photon can acquire mass in 1+1-dimensional QED



Phil Anderson

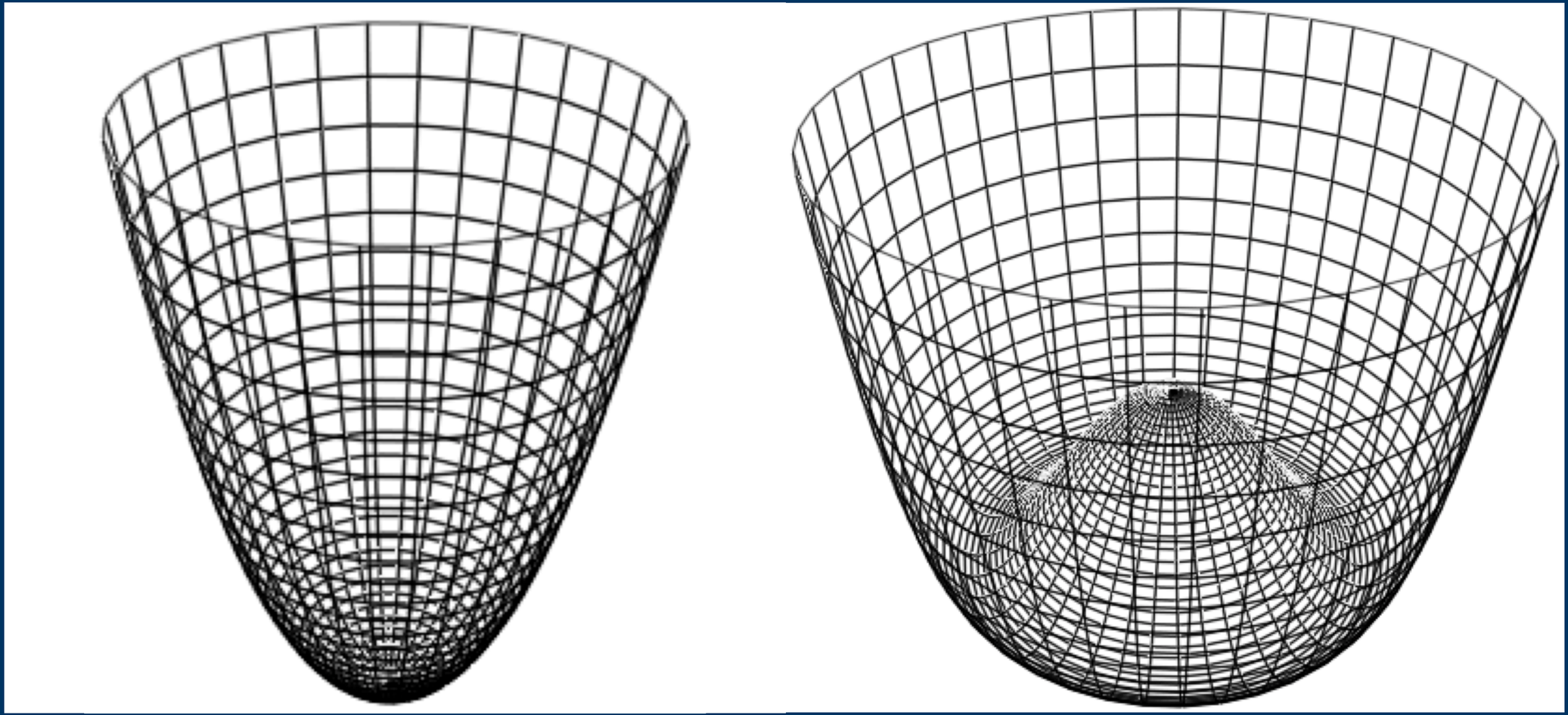
(1963) Superconductor: massive photon, hidden gauge symmetry. Model for strong interactions?

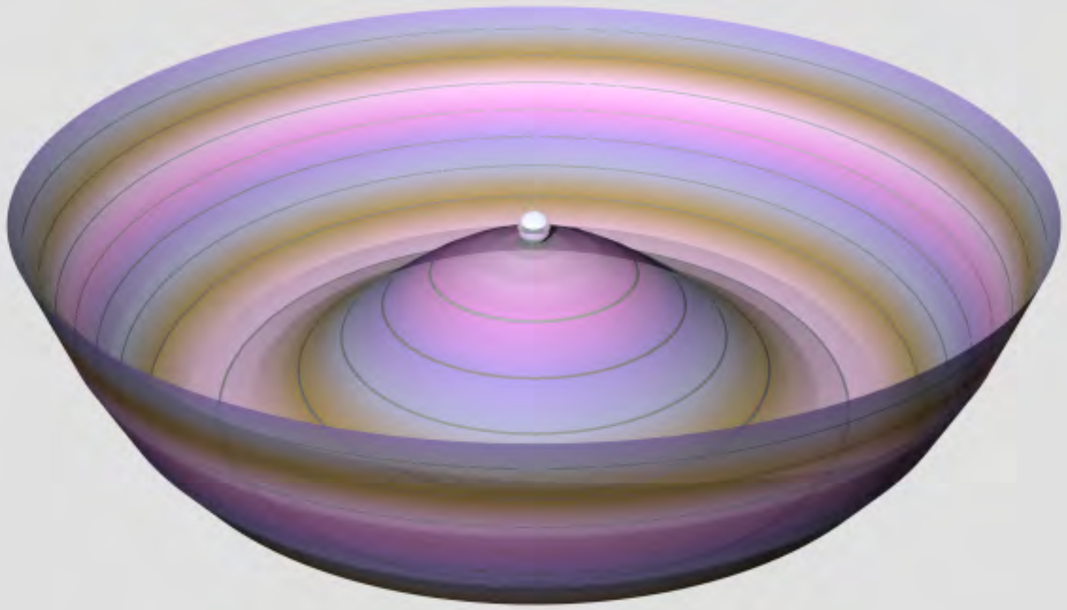
BCS theory (1957): microscopic description of superconductivity

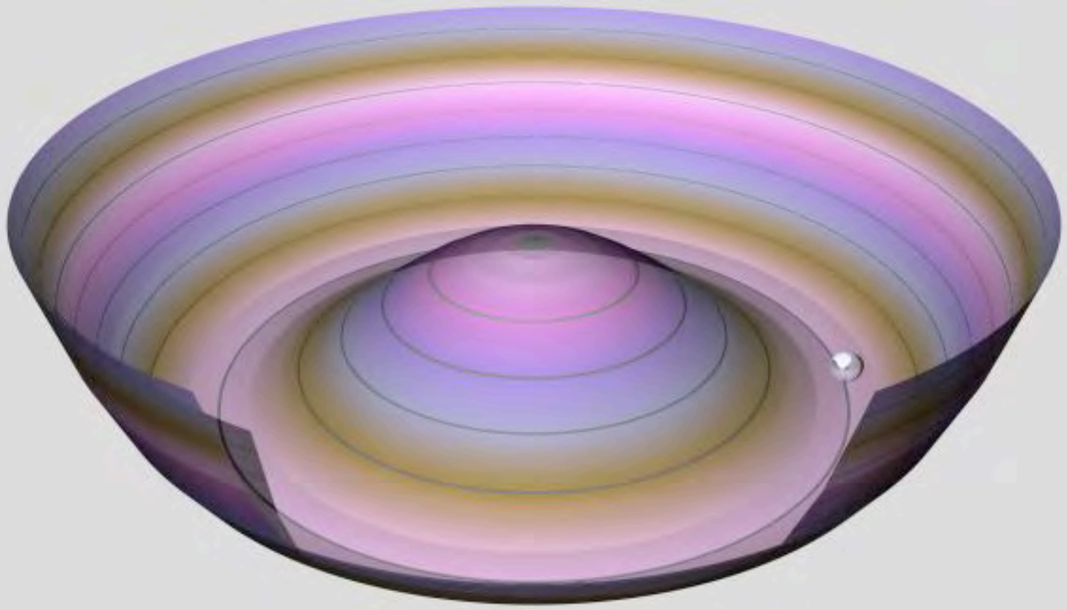
John Bardeen Leon Cooper Robert Schrieffer

Might hiding the gauge symmetry help?

An apparent impediment: the Goldstone Theorem (1961)



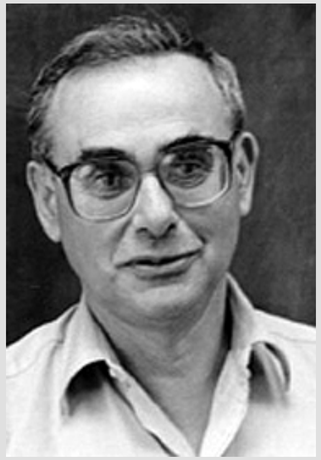




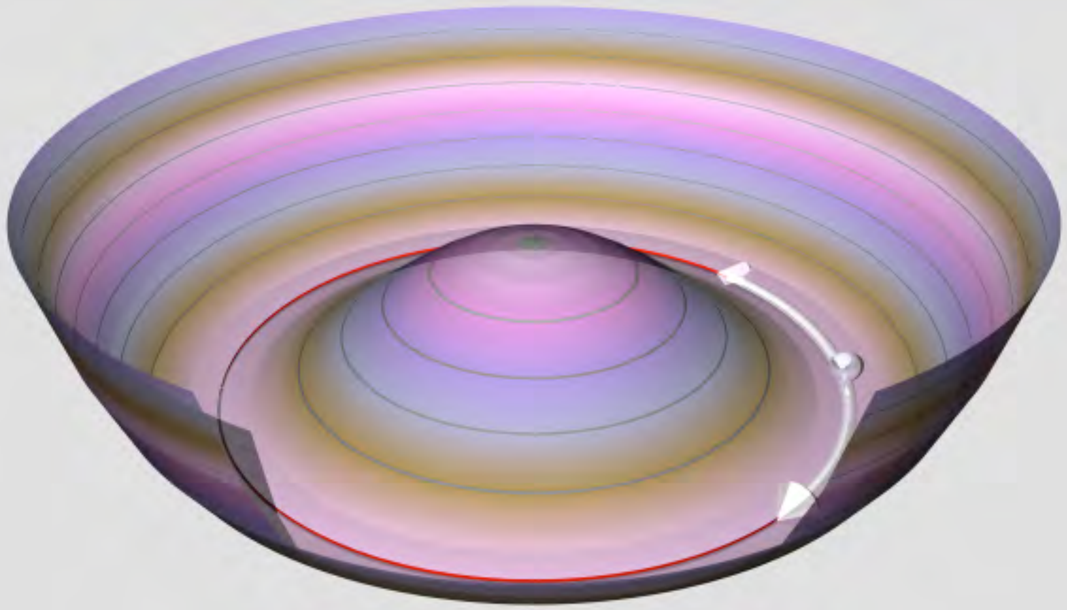
Nambu–Goldstone bosons

Betsy Devine

Yoichiro Nambu



Jeffrey Goldstone

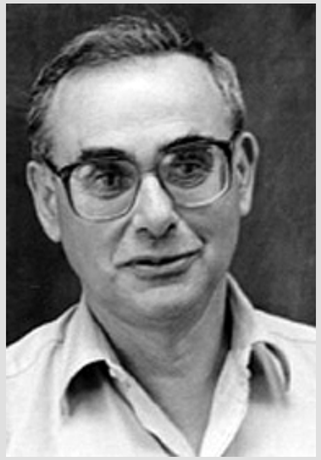


NGBs as spin waves, phonons, pions, …

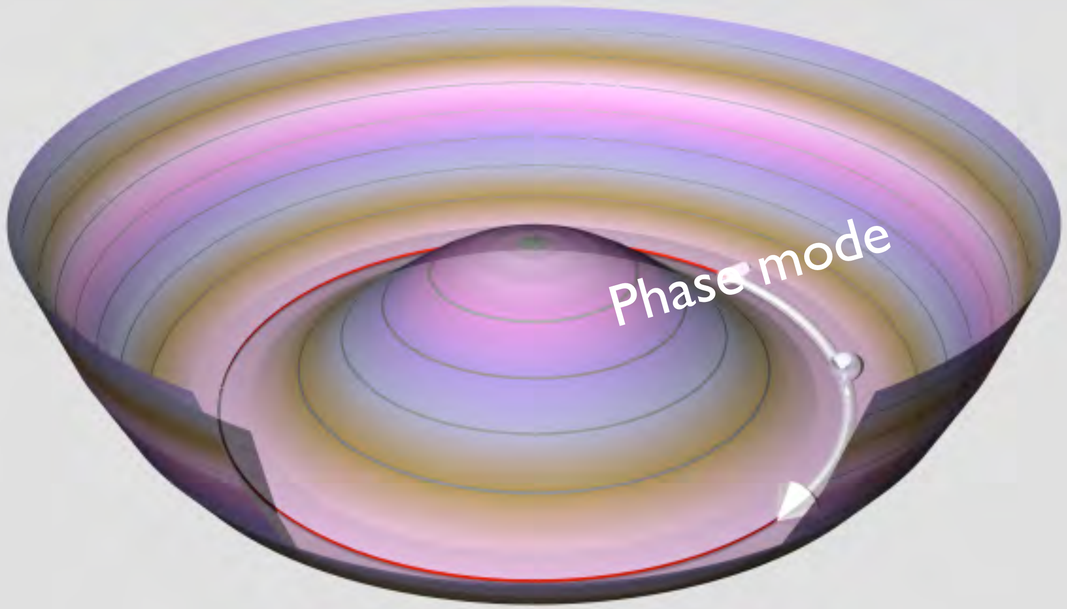
Nambu–Goldstone bosons

Betsy Devine

Yoichiro Nambu

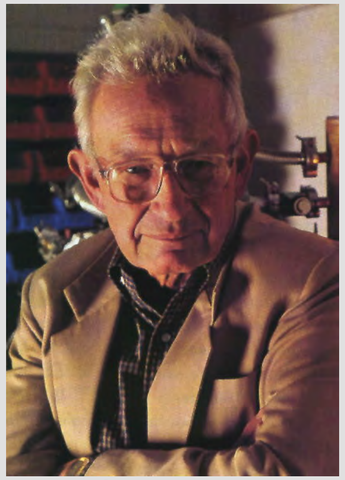


Jeffrey Goldstone

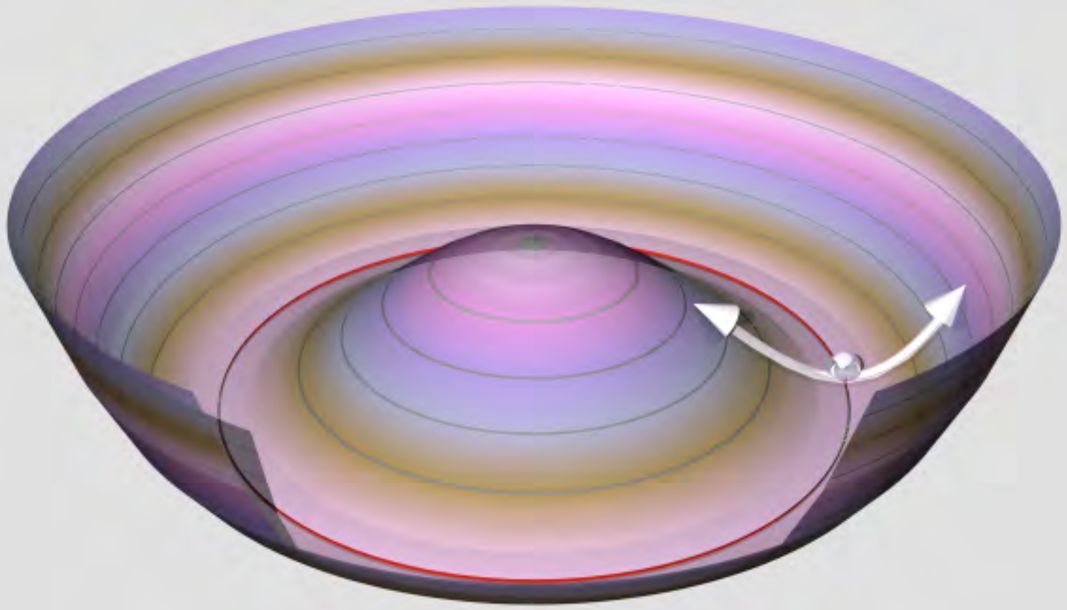


NGBs as spin waves, phonons, pions, . . .

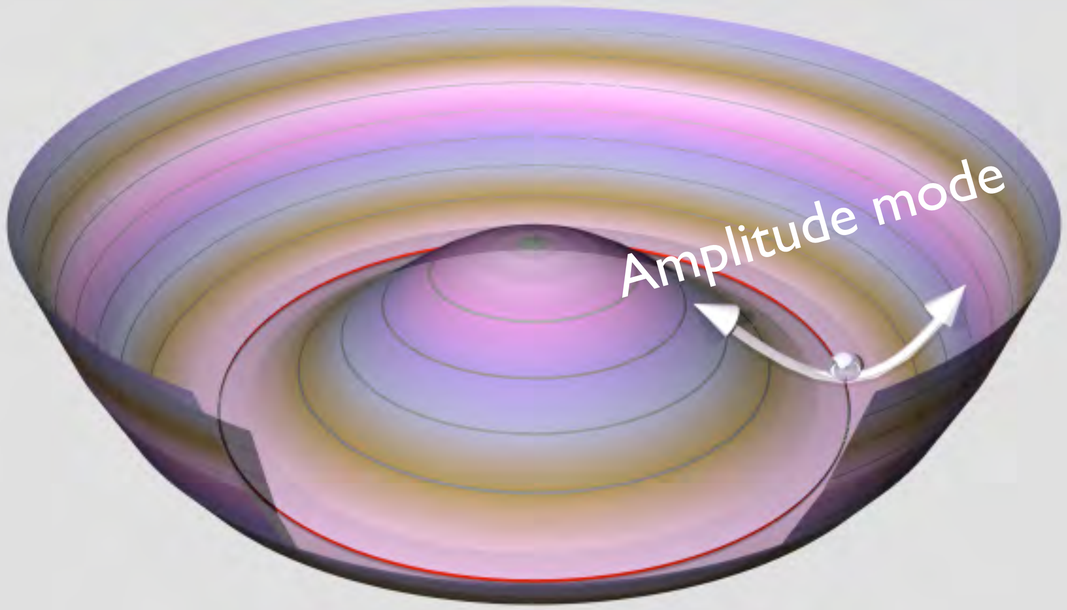
Nikolai Bogoliubov



Phil Anderson



Massive scalar boson



Massive scalar boson

Spontaneously broken gauge symmetry

Sekhar Chivukula

Higgs Kibble† Guralnik† Hagen Englert Brout†

1964– : Goldstone theorem doesn't apply to gauge theories!
Each would-be massless NGB joins with a would-be massless gauge boson to form a massive gauge boson, leaving an incomplete multiplet of massive scalar bosons.

Spontaneous Symmetry Breaking as an origin of gauge-boson mass—some early classics

For the link between gauge invariance and the Meissner effect, see **P. W. Anderson**, "Coherent Excited States in the Theory of Superconductivity: Gauge Invariance and the Meissner Effect," Phys. Rev. 110, 827 (1958); **Y. Nambu,** "Quasi-Particles and Gauge Invariance in the Theory of Superconductivity," Phys. Rev. 117, 648 (1960).

Y. Nambu, "Axial Vector Current Conservation in Weak Interactions," Phys. Rev. Lett. 4, 380 (1960);
with **G. Jona-Lasinio**, "Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. I," Phys. Rev. 122, 345 (1961); "Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. II," Phys. Rev. 124, 246 (1961).

J. Goldstone, "Field theories with « Superconductor » solutions," Nuovo Cim. 19, 154 (1961);
with **A. Salam and S. Weinberg,** "Broken Symmetries," Phys. Rev. 127, 965 (1962).

F. Englert and R. Brout, "Broken Symmetry and the Mass of Gauge Vector Mesons," Phys. Rev. Lett. 13, 321 (1964).

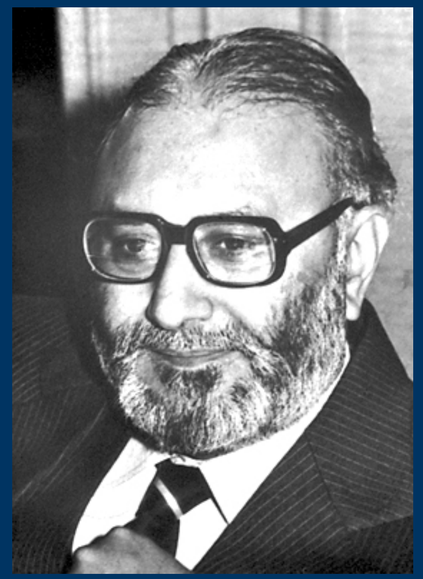
P. W. Higgs, "Broken symmetries, massless particles and gauge fields," Phys. Lett. 12, 132 (1964);
"Broken Symmetries and the Masses of Gauge Bosons," Phys. Rev. Lett. 13, 508 (1964).

G. S. Guralnik, **C. R. Hagen**, **and T.W.B. Kibble**, "Global Conservation Laws and Massless Particles," Phys. Rev. Lett. 13, 585 (1964).

T.W.B. Kibble, "Symmetry Breaking in Non-Abelian Gauge Theories," Phys. Rev. 155, 1554 (1967).

That one zero-mass ill might cancel the other was suggested by analogy with the plasmon theory of the free-electron gas by **P. W. Anderson**, "Plasmons, Gauge Invariance, and Mass," Phys. Rev. 130, 439 (1963).

Steven Weinberg



Abdus Salam

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \tag{2}$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu \partial_\mu L - \bar{R}\gamma^\mu \partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q = T_3 - N_R - \frac{1}{2}N_L$, and the electron number $N = N_R + N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y \equiv N_R + \frac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero dou-

Contrive a vacuum to hide EW symmetry
(need four scalar fields)

"Higgs mechanism" breaks

$$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$$

$$g \qquad\qquad g'$$

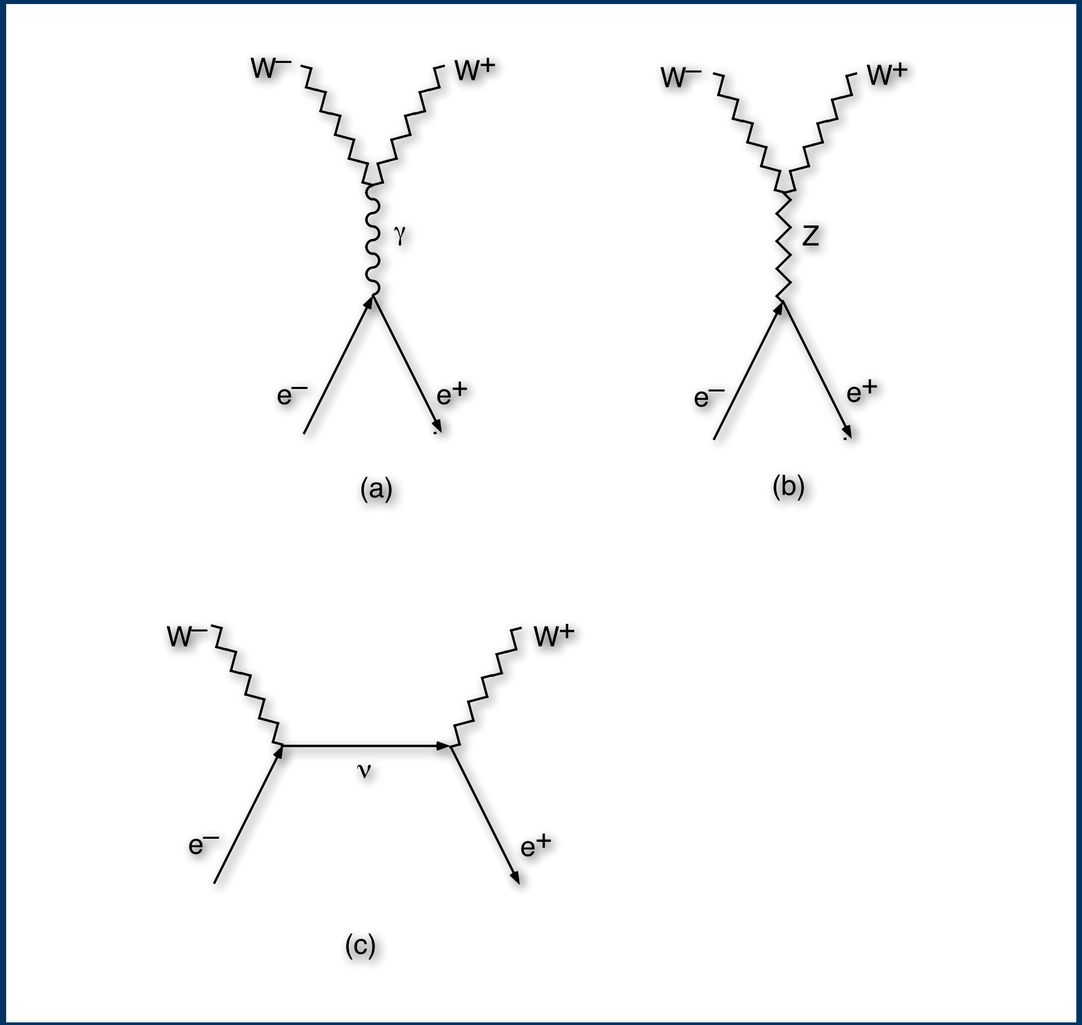
$$M_\gamma = 0;\ M_W = gv/2;\ M_Z = M_W/\cos\theta_W$$

$$\tan\theta_W = g'/g \qquad\qquad v = 246\ \text{GeV}$$

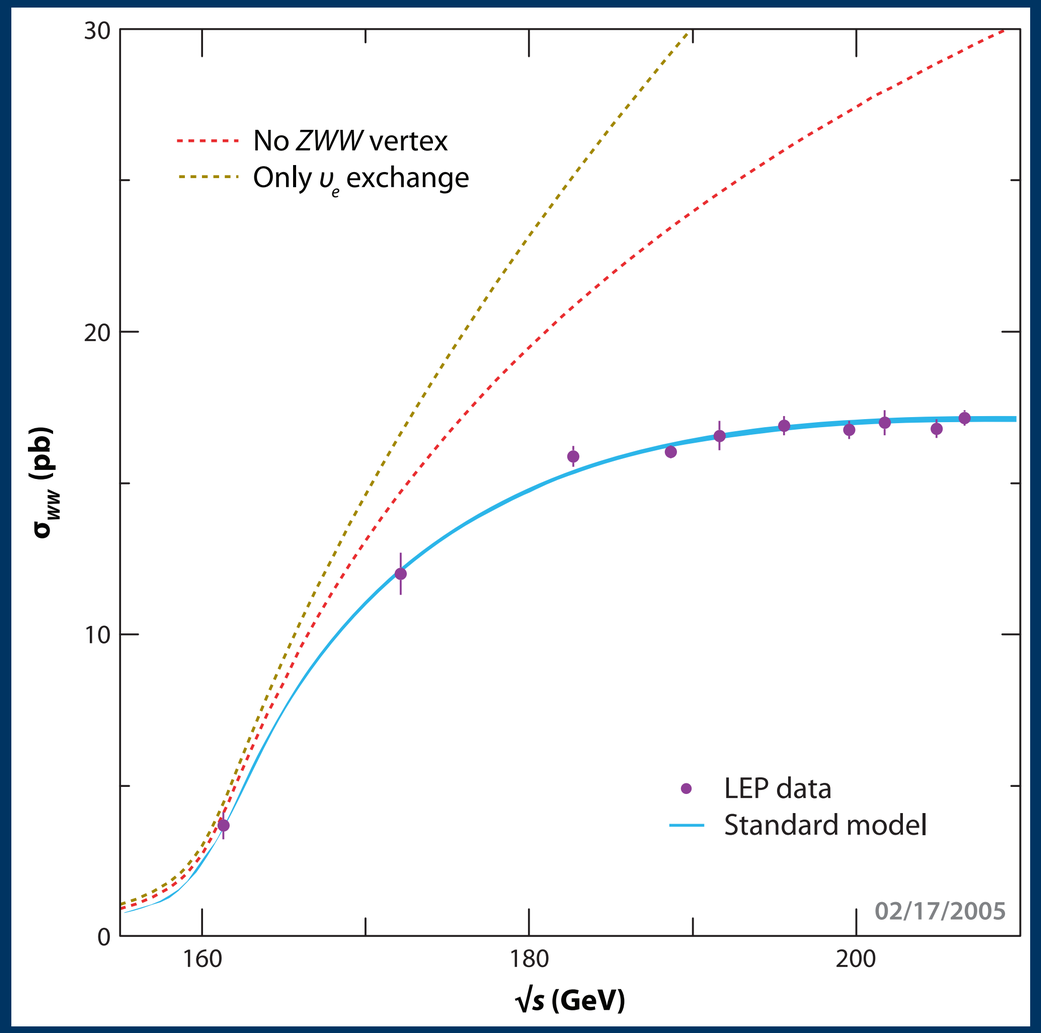
Plus a massive scalar H (mass unspecified)

Gauge symmetry (group-theory structure) tested in

$$e^+e^- \to W^+W^-$$



Electroweak symmetry is real



Fermion mass after SSB (a task for *H*)

By decree, Weinberg adds
interactions between fermions and scalars
that give rise to quark and lepton masses (and mixings).

$$\zeta_e \left[(\overline{e_{\mathsf{L}}} \Phi) e_{\mathsf{R}} + \overline{e_{\mathsf{R}}} (\Phi^\dagger e_{\mathsf{L}}) \right] \rightsquigarrow m_e = \zeta_e v / \sqrt{2}$$

ζ_e : picked to give right mass, not predicted

Fermion mass implies physics beyond standard model!

Highly economical, but is it true?

Incorporating hadrons …

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

Matched quark and lepton doublets
make theory anomaly-free, renormalizable,
and eliminate flavor-changing neutral currents.

"A Model of Leptons": 12 citations in first four years, 13,270 today

Renormalizability of spontaneously broken gauge theories:
't Hooft, Veltman, Lee & Zinn-Justin, et al.

Discovery of neutral-current interactions (1973)
charm (1974–6), τ (1975)
b-quark (1977)
W and *Z* (1982–3)
t-quark (1995)

⋱

4 July 2012: Dawn of the New Age

Four tasks for the standard-model Higgs boson

Hide electroweak symmetry
(distinguish EM, weak interactions)

Give masses to $W^{\pm}$, Z^0

Give masses and mixings to fermions

Keep EW theory from misbehaving

Higgs bosons: incomplete multiplets after SSB

(w_1, w_2, z, h) form O(4) multiplet

w_1, w_2, z become longitudinal W^+, W^-, Z^0

h becomes H, remembers its roots

Role in regulating $W_L W_L$ high-energy behavior, tipping point for $M_H \approx 1$ TeV, …

See end of §III, Phys. Rev. D16, 1519 (1977)

Three Great Questions

How does the scalar potential arise?
(What is the origin of electroweak symmetry breaking?)

What determines fermion masses and mixings?
(How do the Yukawa couplings arise?)

Does the "Higgs mechanism" play a decisive
role elsewhere in particle physics, e.g., unified theories?

Thanks to participants, lecturers, organizers, sponsors!