The Nobel Prize in Physics 2008: Broken Symmetries

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The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2008 with one half to

**Yoichiro Nambu**, Enrico Fermi Institute, University of Chicago, IL, USA

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

and the other half jointly to

**Makoto Kobayashi**, High Energy Accelerator Research Organization (KEK), Tsukuba

**Toshihide Maskawa**, Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Japan

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

PS: Lots of information: [http://nobelprize.org](http://nobelprize.org)
Yoichiro Nambu

Enrico Fermi Institute,
University of Chicago
Chicago, IL, USA
b. 1921 (in Tokyo, Japan)

D.Sc. 1952
University of Tokyo, Japan
Makoto Kobayashi

High Energy Accelerator Research Organization (KEK)
Tsukuba,
b. 1944

Ph.D. 1972
Nagoya University, Japan
Toshihide Maskawa

Kyoto Sangyo University;

Yukawa Institute for Theoretical Physics (YITP)
Kyoto University
Kyoto, Japan
b. 1940

Ph.D. 1967
Nagoya University, Japan
Papers

Symmetry

no change if rotated along vertical axis

Invariant under rotation group $U(1)$
Symmetry

changes if rotated along vertical axis

But $U(1)$ invariance good approximation

Symmetry explicitly broken by the picture
Spontaneously Broken Symmetry

- Pencil balanced on end (on a table) has rotational symmetry about vertical axis.
- Symmetry is broken when pencil falls over: lower energy state
- Special direction is specified.
- But, underlying law of gravity is still symmetrical.
- Pencil could have fallen into any available direction
Spontaneous broken symmetry. The world of this pencil is completely symmetrical. All directions are exactly equal. But this symmetry is lost when the pencil falls over. Now only one direction holds. The symmetry that existed before is hidden behind the fallen pencil.

http://nobelprize.org
Symmetry

Symmetries are very well known in physics (and definitely in particle physics)

- Heisenberg, Wigner, Eckart, Yang, Mills, Glashow, Weinberg, Salam, …

- **Nambu**: Introduced the concept of *spontaneously broken symmetries* into particle physics

- **Kobayashi and Maskawa**: Proposed the mechanism by which the combined *charge-conjugation–parity (CP)* symmetry is broken in the Standard Model
Spontaneous symmetry breaking

Magnets (e.g. in iron):

Symmetry:

With interactions:

Low energy:

High energy:
Spontaneous symmetry breaking

a generic state
Spontaneous symmetry breaking

the ground state
Spontaneous symmetry breaking

No: A ground state
Spontaneous symmetry breaking

A ground state: choice of vacuum breaks the symmetry

Spontaneous symmetry breaking
Spontaneous symmetry breaking

A very low energy excitation: spin wave
Spontaneous symmetry breaking

A very low energy excitation: spin wave
A collective excitation: quasiparticle
Nambu and Superconductivity

- Superconductivity: conductivity goes to zero below a critical temperature
- Discovered by Kamerlingh-Onnes in 1911
- Meisnner: expel magnetic fields 1933
- Landau-Ginzburg-Abrikosov: Phenomenological Theory (scalar field)
- Explained by Bardeen, Cooper and Schrieffer by Cooper pair condensation 1957
- Bogolyubov 1958, (Bogolyubov transformation)
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- Bogolyubov 1958, (Bogolyubov transformation)
- Note the many other Nobel Prizes here
Nambu and Superconductivity

- Condensed Cooper Pairs: **Ground State is Charged**
- What about **Gauge Invariance**?
Condensed Cooper Pairs: **Ground State is Charged**

What about **Gauge Invariance**?

---

**Electromagnetic Gauge Invariance**

- Wave function: \( \psi(x) \rightarrow e^{-i\alpha(x)}\psi(x) \)

  does not change \( |\psi(x)|^2 \)

- \( \vec{A}(x) \rightarrow \vec{A}(x) - \vec{\nabla}\alpha(x) \) and \( V(x) \rightarrow V(x) - \frac{\partial\alpha(x)}{\partial t} \)

  do not change \( \vec{E}(x) \) and \( \vec{B}(x) \)

- Minimal coupling: both invariances belong together

- Requiring gauge invariance determines the form of the interaction
Nambu and Superconductivity

- He used the Feynman-Dyson methods for QuantumElectroDynamics (QED)
- Reformulated BCS as a generalized Hartree-Fock ground state
  - When deriving Green functions (which lead to amplitudes) you also need to introduce the loop graphs both in the interaction vertex and in the selfenergies
  - When you do that all Ward identities are satisfied
  - Hence everything is gauge invariant as should be
Nambu and Superconductivity

- He used the Feynman-Dyson methods for Quantum Electro Dynamics (QED)
- Reformulated BCS as a generalized Hartree-Fock ground state
  - The photon “mixes” with the available electron/hole states
  - Longitudinal mode of the photon couples to the collective excitations
  - In effect produces a mass for the photon  ⇒  Meissner effect
Nambu and Superconductivity

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- Brout-Englert, Higgs, Guralnik-Hagen-Kibble: generalize to Yang-Mills
- Weinberg, Salam apply to Glashow’s neutral current model: the Standard Model
First an aside: The Weak Interaction and Parity

- Parity \((P)\): \( \vec{x} \rightarrow -\vec{x} \)

- related to mirror symmetry

- Lee and Yang 1956: No experiment for \(P\) in weak interaction and can solve \(\tau\theta\) puzzle

- Suggested \(^{60}\text{Co}\) and \(\mu\)-decay: immediately seen
First an aside: The Electromagnetic and Weak Interaction

- Electromagnetic coupling to electron:
  \[ A_\mu J^\mu = A_\mu \overline{e} \gamma^\mu e \quad (e \equiv \psi_e) \]

- Current is conserved:
  \[ \frac{\partial J^\mu}{\partial x^\mu} = 0 \Rightarrow \]
  Matrix element of \( J^\mu \) at \( q^2 = 0 \) is \( \equiv 1 \).

- Weak interaction is (leptonic \( \mu \) decay)
  \[
  \frac{G_F}{\sqrt{2}} J(\mu)_\rho J(e)^\rho = \frac{G_F}{\sqrt{2}} \overline{\mu} \gamma^\rho (1 - \gamma_5) \nu_\mu \overline{\nu}_e \gamma^\rho (1 - \gamma_5) e
  \]

- Feynman-Gell-Mann, Marshak-Sudarshan: \( V_\rho - A_\rho \)

- \( V_\rho \) and \( A_\rho \) conserved (CVC and CAC) for hadrons \( \Rightarrow \)
  \( \equiv 1 \) at \( q^2 = 0 \).
Nambu: SSB in the Strong Interaction

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- Feynman-Gell-Mann, Marshak-Sudarshan: \( V_\rho = A_\rho \)

- \( V_\rho \) and \( A_\rho \) conserved (CVC and CAC) for hadrons \( \Rightarrow \)
  \( \equiv 1 \) at \( q^2 = 0 \).

- Neutron decay:
  \[
  \frac{G_F}{\sqrt{2}} 0.97 \bar{p} \gamma^\rho (1 - 1.27 \gamma_5) n \bar{e} \gamma^\rho (1 - \gamma_5) \nu_e
  \]
$g_A = 1.27 \neq 1$

Solved simultaneously by Gell-Mann-Levy and Nambu

PCAC: Partially Conserved Axial Current
Nambu: SSB in the Strong Interaction

- \( g_A = 1.27 \neq 1 \)
- Solved simultaneously by Gell-Mann-Levy and Nambu
- PCAC: Partially Conserved Axial Current

A CAC & \( g_A \neq 0 \):

\[
\bar{p} \left( g_A F_1(q^2) \right) \left( \gamma_\mu \gamma_5 - \frac{2M_N q_\mu}{q^2} \gamma_5 \right) n
\]

- But has pseudoscalar coupling and massless pole: ruled out
Nambu: SSB in the Strong Interaction

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But has pseudoscalar coupling and massless pole: ruled out

$$\bar{p} \left( g_A F_1(q^2) \right) \left( \gamma_\mu \gamma_5 - \frac{2M_N q_\mu}{(q^2 + m_\pi^2)} \gamma_5 \right) n$$
Nambu: SSB in the Strong Interaction

Consequences:

- PCAC: \[ \frac{\partial A^\rho}{\partial x^\rho} = i m_\pi^2 F_\pi \phi_\pi \]

- Partially: conserved when \( m_\pi^2 \to 0 \)

- \( G_\pi = \frac{\sqrt{2} M_N g_A}{F_\pi} \), the pion coupling to the nucleon is related to the pion decay constant and \( g_A \)

Golberger-Treiman relation
Consequences:

- **PCAC:** \[ \frac{\partial A^\rho}{\partial x^\rho} = im_\pi^2 F_\pi \phi_\pi \]

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- \( G_\pi = \frac{\sqrt{2} M_N g_A}{F_\pi} \), the pion coupling to the nucleon is related to the pion decay constant and \( g_A \)

  - Golberger-Treiman relation

- Similar suggestion also for the strangeness changing hyperon decays and the pion to Kaon

- Both papers also suggested that there should be an axial variant of isospin symmetry: exact for \( m_\pi \to 0 \)

- Isospin: \( SU(2) \) symmetry from interchanging \( p \) and \( n \)

Wigner
Further developments

- He realized that if an exact symmetry is spontaneously broken there must be a massless particle.
- Also suggested by Goldstone (Nambu-Goldstone Bosons).
- Proven by Goldstone-Salam-Weinberg.
Goldstone Modes

**UNBROKEN:** $V(\phi)$

Only massive modes around lowest energy state (=vacuum)

**BROKEN:** $V(\phi)$

Need to pick a vacuum

$\langle \phi \rangle \neq 0$: Breaks symmetry

No parity doublets

Massless mode along ridge
Goldstone Modes

Also here: low energy excitations
Goldstone Modes

Also here: low energy excitations

Overall direction is a symmetry

\[ \theta(x) \rightarrow \theta(x) + \Theta \]

No Change

Interactions must vanish if \( \theta(x) \) is constant

Low energy: no interactions
Nambu: SSB in the Strong Interaction

- Soft Pions and Current Algebra:

\[ \frac{\partial A^\rho}{\partial x^\rho} = i m_\pi^2 F_\pi \phi_\pi \]

- This means that an axial symmetry rotation connects processes with different numbers of pions
Soft Pions and Current Algebra:

\[
\frac{\partial A^\rho}{\partial x^\rho} = i m_\pi^2 F_\pi \phi_\pi
\]

This means that an axial symmetry rotation connects processes with different numbers of pions.

This together with the small interactions at low energies allows for a systematic expansion for processes only involving the low-energy excitations.

Chiral Perturbation Theory is the modern way to use this.
How does this fit in with QCD

Chiral Symmetry

QCD: 3 light quarks: equal mass: interchange: $U(3)_V$

But $\mathcal{L}_{QCD} = \sum_{q=u,d,s} [i\bar{q}_L \gamma^\mu q_L + i\bar{q}_R \gamma^\mu q_R - m_q (\bar{q}_R q_L + \bar{q}_L q_R)]$

So if $m_q = 0$ then $U(3)_L \times U(3)_R$.

$\begin{pmatrix} u_L \\ d_L \\ s_L \end{pmatrix} \rightarrow U_L \begin{pmatrix} u_L \\ d_L \\ s_L \end{pmatrix}$ and $\begin{pmatrix} u_R \\ d_R \\ s_R \end{pmatrix} \rightarrow U_R \begin{pmatrix} u_R \\ d_R \\ s_R \end{pmatrix}$

Can also see that left right independent via

$v < c, m_q \neq 0 \implies v = c, m_q = 0 \implies$
How does this fit in with QCD

Chiral Symmetry

QCD: 3 light quarks: equal mass: interchange: $U(3)_V$

But $\mathcal{L}_{QCD} = \sum_{q=u,d,s} [i\bar{q}_L D_L q_L + i\bar{q}_R D_R q_R - m_q (\bar{q}_R q_L + \bar{q}_L q_R)]$

So if $m_q = 0$ then $U(3)_L \times U(3)_R$.

- Hadrons do not come in parity doublets: symmetry must be broken.
- A few very light hadrons: $\pi^0 \pi^+ \pi^-$ and also $K, \eta$.
- Both can be understood from spontaneous Chiral Symmetry Breaking.
- Anomaly: really $SU(3)_L \times SU(3)_R$.
Kobayashi and Maskawa

Let’s extend now $P$ and

$$\frac{G_F}{\sqrt{2}} 0.97 \bar{p} \gamma^\rho (1 - 1.27 \gamma_5) n \bar{e} \gamma^\rho (1 - \gamma_5) \nu_e$$
Let’s extend now $P$ and $G$

$$\frac{G_F}{\sqrt{2}} \times 0.97 \bar{P}\gamma^\rho \left(1 - 1.27 \gamma_5\right) n \bar{e}\gamma^\rho \left(1 - \gamma_5\right) \nu_e$$

- $P$ is broken by the weak interaction
- $CP$ is not
- $C$: Charge conjugation, replace everyone by their antiparticle
- $CP$ conservation still allows to solve the $\tau \theta$ puzzle
Let’s extend now $P$ and

$$\frac{G_F}{\sqrt{2}} 0.97 \overline{p} \gamma^\rho (1 - 1.27 \gamma_5) n \overline{e} \gamma^\rho (1 - \gamma_5) \nu_e$$

- $P$ is broken by the weak interaction
- $CP$ is not
- $C$: Charge conjugation, replace everyone by their antiparticle
- $CP$ conservation still allows to solve the $\tau \theta$ puzzle
- Experimentally $CP$ is violated a little bit in Kaons Cronin-Fitch 1964
- $K^0(\bar{s}d)$ and $\overline{K^0}(d\bar{s})$ mix through the weak interaction, eigenstates $K_L$ and $K_S$
- A tiny but well measured mass difference is a consequence
The 0.97

Suggestion: the weak current for hadrons really is the same as for leptons but it mixes $\Delta S = 1$ and $\Delta S = 0$
Gell-Mann-Levy 1960, Cabibbo 1963

\[ J_\rho = \cos \theta_C J_\rho^{\Delta S=0} + \sin \theta_C J_\rho^{\Delta S=1} \]

- $\Delta S = 0$ current: with $p$ and $n$,
- $\Delta S = 1$ current: with $p$ and $\Lambda$
- And the same for the coupling of pion to kaon

With $\sin \theta_C \approx 0.22$ this explained the 0.97 and the by 1963 much better measured $\Delta S = 1$ decays of Kaon and Hyperons.
Quarks came

In quark language now weak interaction from $W^\pm$ exchange and the vertex is

$$W^+ \mu \bar{u} \gamma_\mu (1 - \gamma_5) (\cos \theta_C d + \sin \theta_C s)$$

A mechanism for getting the $K_L - K_S$ mass difference is

Result is way too large
Add another quark

\[
\begin{align*}
W^+\mu \bar{u}\gamma_\mu (1 - \gamma_5) (\cos \theta_C d + \sin \theta_C s) + \\
W^+\mu \bar{c}\gamma_\mu (1 - \gamma_5) (-\sin \theta_C d + \cos \theta_C s)
\end{align*}
\]

The mechanism is now

Result is zero if \( m_u = m_c \); the vertical lines have
\[\sin \theta_C \cos \theta_C - \cos \theta_C \sin \theta_C \] (GIM mechanism)

Fits for \( m_c \approx 1.5 GeV/c^2 \) (Gaillard-Lee)

Charm discovered 1974 Richter-Ting
The standard model: interactions with $W^\mu$ and the masses:

$i, j, k, l = 1, 2, \text{ later } 1, 2, 3$

$u_1 = u, u_2 = c, u_3 = t, d_1 = d, d_2 = s, d_3 = b$

$W$ Interactions:

$$W^+ \mu \sum_i \bar{u}^W_{Li} \gamma_\mu d^W_{Li} + h.c.$$  

Mass terms ($\nu$ is the Higgs vacuum expectation value)

$$-\nu \sum_{ij} \bar{d}^W_{Li} \lambda^D_{ij} d^W_{Rj} - \nu \sum_{ij} \bar{u}^W_{Li} \lambda^U_{ij} u^W_{Rj} + h.c.$$
\( \theta_C \) in the Standard Model

\[
-v \sum_{ij} \overline{d}_L^i \lambda^D_{ij} d_R^j - v \sum_{ij} \overline{u}_L^i \lambda^U_{ij} u_R^j + \text{h.c.}
\]

- \( v\lambda^U \) and \( v\Lambda^D \) are complex 2 by 2 (3 by 3) matrices
- Diagonalization is always possible by two complex matrices each
- \( V_L^U v\lambda^U V_R^{U\dagger} = \text{diag}(m_u, m_c, m_t) \)
  \[
  V_L^D v\lambda^D V_R^{D\dagger} = \text{diag}(m_d, m_s, m_b)
  \]
\( \theta_C \) in the Standard Model

\[ -v \sum_{ij} \bar{d}_{Li} \lambda_{ij}^D d_{Rj} - v \sum_{ij} \bar{u}_{Li} \lambda_{ij}^U u_{Rj} + \text{h.c.} \]

\( \nu \lambda^U \) and \( \nu \Lambda^D \) are complex 2 by 2 (3 by 3) matrices.

Diagonalization is always possible by two complex matrices each:

\[ V^U_L \nu \lambda^U V^U_R \dagger = \text{diag}(m_u, m_c, m_t) \]
\[ V^D_L \nu \lambda^D V^D_R \dagger = \text{diag}(m_d, m_s, m_b) \]

Define:

\[ u^W_{Li} = \sum_j V^U_{Lij} u_{Lj} \quad \text{and} \quad u^W_{Ri} = \sum_j V^U_{Rij} u_{Rj}, \]
\[ d^W_{Li} = \sum_j V^D_{Lij} d_{Lj}, \quad d^W_{Ri} = \sum_j V^D_{Rij} d_{Rj} \]

mass eigenstates

and substitute
$\theta_C$ in the Standard Model

$$-\nu \sum_{ijkl} \bar{d}_{Li} V_{Lij}^D \lambda_{jk}^D V_{Rkl}^{D\dagger} d_{Rk} - \nu \sum_{ijkl} \bar{u}_{Li} V_{Lij}^U \lambda_{jk}^U V_{Rkl}^{U\dagger} u_{Rk}$$

$$+h.c. = - \sum_i \bar{d}_{Li} m_i d_{Ri} - \sum_i \bar{u}_{Li} m_{ui} u_{Ri} + h.c.$$  

Phase invariance left:

- $d_{Li} \rightarrow e^{i\alpha_i} d_{Li}$, $d_{Ri} \rightarrow e^{-i\alpha_i} d_{Ri}$
- $u_{Li} \rightarrow e^{i\beta_i} u_{Li}$, $u_{Ri} \rightarrow e^{-i\beta_i} u_{Ri}$
\[ -v \sum_{ijkl} \overline{d}_{Li} V^D_{Lij} \lambda^D_{jk} V^D_{Rkl} d_{Rk} - v \sum_{ijkl} \overline{u}_{Li} V^U_{Lij} \lambda^U_{jk} V^U_{Rkl} u_{Rk} \]

\[ + h.c. = - \sum_i \overline{d}_{Li} m_d_i d_{Ri} - \sum_i \overline{u}_{Li} m_u_i u_{Ri} + h.c. \]

The \( W \) Interactions: \[ W^{+\mu} \sum_i \overline{u}_L^W \gamma_\mu d_L^W + h.c. \]

\[ W^{+\mu} \sum_{ijkl} \overline{u}_{Li} \gamma_\mu V^U_{Lij} V^D_{Ljk} d_{Lk} + h.c. \]
\[ -\nu \sum_{ijkl} \overline{d}_{Li} V_{Lij}^D \lambda_{jk}^D V_{Rkl}^{D\dagger} d_{Rk} - \nu \sum_{ijkl} \overline{u}_{Li} V_{Lij}^U \lambda_{jk}^U V_{Rkl}^{U\dagger} u_{Rk} \]

\[ + h.c. = - \sum_i \overline{d}_{Li} m_d d_{Ri} - \sum_i \overline{u}_{Li} m_u u_{Ri} + h.c. \]

The \( W \) Interactions:

\[ W^+ \mu \sum_i \overline{u}_{Li}^W \gamma_\mu d_{Li}^{W\dagger} + h.c. \]

become

\[ W^+ \mu \sum_{ijkl} \overline{u}_{Li} \gamma_\mu V_{Lij}^U V_{Ljk}^{D\dagger} d_{Lk} + h.c. \]

- \( V_{CKM} = V_L^U V_L^{D\dagger} \) is a unitary matrix
- All other terms in the Lagrangian get \( V_L^U V_L^{U\dagger} = 1, \ldots \)
θ_C in the Standard Model

The two generation case ($V_{CKM} = V$)

Flavours only: 

$$\left( \begin{array}{cc} \bar{u}_L & \bar{c}_L \end{array} \right) V \left( \begin{array}{c} d_L \\ s_L \end{array} \right)$$

$V$ is a general 2 by 2 unitary matrix.
\( \theta_C \) in the Standard Model

The two generation case \((V_{CKM} = V)\)

Flavours only: \[
\begin{pmatrix}
\bar{u}_L & \bar{c}_L
\end{pmatrix}
\begin{pmatrix}
V
\end{pmatrix}
\begin{pmatrix}
d_L \\
s_L
\end{pmatrix}
\]

\( V \) is a general 2 by 2 unitary matrix.

- Use \( \alpha_i \) and \( \beta_i \) to make \( V_{11}, V_{12} \) and \( V_{21} \) real:

\[
\begin{pmatrix}
\bar{u}_L & \bar{c}_L
\end{pmatrix}
\begin{pmatrix}
e^{-i\beta_1 \bar{u}_L} e^{-i\beta_2 \bar{c}_L} \\
V_{11} & V_{12} \\
V_{21} & V_{22}
\end{pmatrix}
\begin{pmatrix}
e^{i\alpha_1} d_L \\
e^{i\alpha_2} s_L
\end{pmatrix} = 
\begin{pmatrix}
e^{i(\alpha_1-\beta_1)} V_{11} & e^{i(\alpha_2-\beta_1)} V_{12} \\
e^{i(\alpha_1-\beta_2)} V_{21} & e^{i(\alpha_2-\beta_2)} V_{22}
\end{pmatrix}
\begin{pmatrix}
d_L \\
s_L
\end{pmatrix}
\]

- \( \alpha_2 - \beta_2 = (\alpha_2 - \beta_1) + (\alpha_1 - \beta_2) - (\alpha_1 - \beta_1) \)
The two generation case \((V_{CKM} = V)\)

Flavours only: 
\[
\left( \begin{array}{c}
  \bar{u}_L \\
  \bar{c}_L \\
\end{array} \right) 
V 
\left( \begin{array}{c}
  d_L \\
  s_L \\
\end{array} \right)
\]

\(V\) is a general 2 by 2 unitary matrix.

- Use \(\alpha_i\) and \(\beta_i\) to make \(V_{11}, V_{12}\) and \(V_{21}\) real
- Unitary implies \(\sum_i V_{ik}^* V_{il} = \delta_{il}\)

\[
V = \left( \begin{array}{cc}
  \cos \theta_C & \sin \theta_C \\
  - \sin \theta_C & \cos \theta_C \\
\end{array} \right)
\]

- This gives exactly what we had before
Bold suggestion: add a third generation (remember charm not discovered)

Flavours only: \( \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix} V \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \)

\( V \) is a general 3 by 3 unitary matrix.
Bold suggestion: add a third generation (remember charm not discovered)

- Flavours only: \( \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix} V \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \)

- \( V \) is a general 3 by 3 unitary matrix.

- Use \( \alpha_i \) and \( \beta_i \) to make \( V_{11}, V_{12}, V_{13}, V_{21} \) and \( V_{31} \) real

- Unitary implies \( \sum_i V^*_{ik} V_{il} = \delta_{il} \)

\[
V = \begin{pmatrix}
c_1 & -s_1 c_3 & -s_1 s_3 \\
s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i \delta} & c_1 c_2 s_3 + s_2 c_3 e^{i \delta} \\
s_1 s_2 & c_1 s_2 c_3 + s_2 s_3 e^{i \delta} & c_1 s_2 s_3 - c_2 c_3 e^{i \delta}
\end{pmatrix}
\]

- \( c_i = \cos \theta_i, \ s_i = \sin \theta_i \)
This extra $e^{i\delta}$ makes the Lagrangian intrinsically complex (i.e. not removable by phase redefinitions).

This implies $CP$ violation.

It can explain $CP$ violation that was seen in kaon decays via box diagrams.
This extra $e^{i\delta}$ makes the Lagrangian intrinsically complex (i.e. not removable by phase redefinitions)

This implies $CP$ violation

can explain $CP$ violation that was seen in kaon decays via box diagrams

What has happened since

Third generation discovered

C. Jarlskog: easy way to see from $\lambda^U$ and $\lambda^D$ if $CP$ violation is there

Many more predictions have been seen
The predictions: 1

There is another type of $CP$ violation in Kaon decays: direct $CP$ violation from Penguin diagrams:

\[ K^0 \rightarrow W, \gamma, Z, g \rightarrow \pi^+, \pi^-, \pi^0 \pi^0 \]
There is another type of $CP$ violation in Kaon decays: direct $CP$ violation from Penguin diagrams:

$K^0 \rightarrow \gamma, Z, g \rightarrow \pi^+\pi^-, \pi^0\pi^0$  

Seen in 1999 by KTeV at Fermilab and NA48 at CERN (earlier at NA31 CERN in 1988 not confirmed by Fermilab experiment)
The origin of penguins

Told by John Ellis:

Mary K. [Gaillard], Dimitri [Nanopoulos], and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976. The penguin name came in 1977, as follows.

In the spring of 1977, Mike Chanowitz, Mary K. and I wrote a paper on GUTs [Grand Unified Theories] predicting the $b$ quark mass before it was found. When it was found a few weeks later, Mary K., Dimitri, Serge Rudaz and I immediately started working on its phenomenology.

That summer, there was a student at CERN, Melissa Franklin, who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.

For some time, it was not clear to me how to get the word into this $b$ quark paper that we were writing at the time. Later, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.

John Ellis in Mikhail Shifman, *ITEP Lectures in Particle Physics and Field Theory*, hep-ph/9510397
More predictions

In $B$ meson decays you can have all three generations at tree level in a process. $CP$ violations can (and are) much larger.

$B^0 \to W^+ c s \to J/\psi = \bar{c} c K_S$

Observed at the predicted level in many processes.
More predictions

- In $B$ meson decays you can have all three generations at tree level in a process. $CP$ violations can (and are) much larger

\[ J/\psi = \bar{c}c \]

Observed at the predicted level in many processes

- Penguins also contribute and again in many places
- has led to great confidence in CKM picture both for the angles and the $CP$ violation part
Results

- Parametrization of $V_{CKM}$:

$$
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
$$

The Unitarity triangle of three complex numbers

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \text{ (more exist)}$$
Results

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The Unitarity triangle of three complex numbers

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$ (more exist)

- $|V_{us}| \approx 0.2; |V_{cd}| \approx 0.04$ and $|V_{ub}| \sim 0.003$

Approximate Wolfenstein parametrization:

$$
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
$$

- All three side are of order $\lambda^3$
Results

Each number is itself an average of several measurements.
Conclusion

I hope I have given you a feeling for what these people have accomplished and what the physics behind is