Yoichiro Nambu exploring Spontaneous Symmetry Breaking

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‘One day which was more than ten years ago, E. G. C. Sudarshan and I were in a car together near Chicago. In our conversation he started asking why I had not worked on gravity. “Don’t you think”, he confronted me in the next breath, “that the goal of physics is to find general principles?” Thereupon I answered, “Right now, I am more interested in substance than principle.”’

— from Bull. Phys. Soc. Japan, 32, 773 (1977)

1950’s:

What is the structure of the nuclear force ?

Pion exchange is a contribution, but it is not sufficient.

What other ingredients are required ?

1958: a clue from the weak interaction:

Feynman-Gell-Mann , Marshak-Sudarshan theory of V-A

$$\Delta\mathcal{L} = \frac{4G_F}{\sqrt{2}} J^+_\mu J^{-\mu}$$

leptons: $$J^{+\mu} = \overline{L}\gamma^\mu (\frac{1-\gamma^5}{2})\tau^+ L$$

hadrons: $$J^{+\mu} = \overline{N}\gamma^\mu (\frac{1-\gamma^5}{2})\tau^+ N$$

The nucleon vector current is not renormalized, so

$$G_F = G_\mu$$

The axial isospin current is renormalized,

$$\langle p| \overline{N}\gamma^\mu\gamma^5\tau^+ N |n\rangle = g_A \overline{u}(p)\gamma^\mu\gamma^5 u(n) + \cdots$$

Goldberger-Treiman relation

$$g_A m_N = f_\pi g_{\pi NN}$$

Gell-Mann-Lévy (1960)

The axial-vector current is apparently not conserved. But, the divergence of the axial current has the quantum numbers of the pion, so we can associate

$$\partial_\mu(\overline{N}\gamma^\mu\gamma^5\tau^+N) = \sqrt{2}a\ \pi^+$$

The relation to the pion weak decay matrix element gives

$$a = f_\pi m_\pi^2$$

and, from this, we can coherently derive the Goldberger-Treiman relation.

A concrete example of this physics can be found in the linear σ model

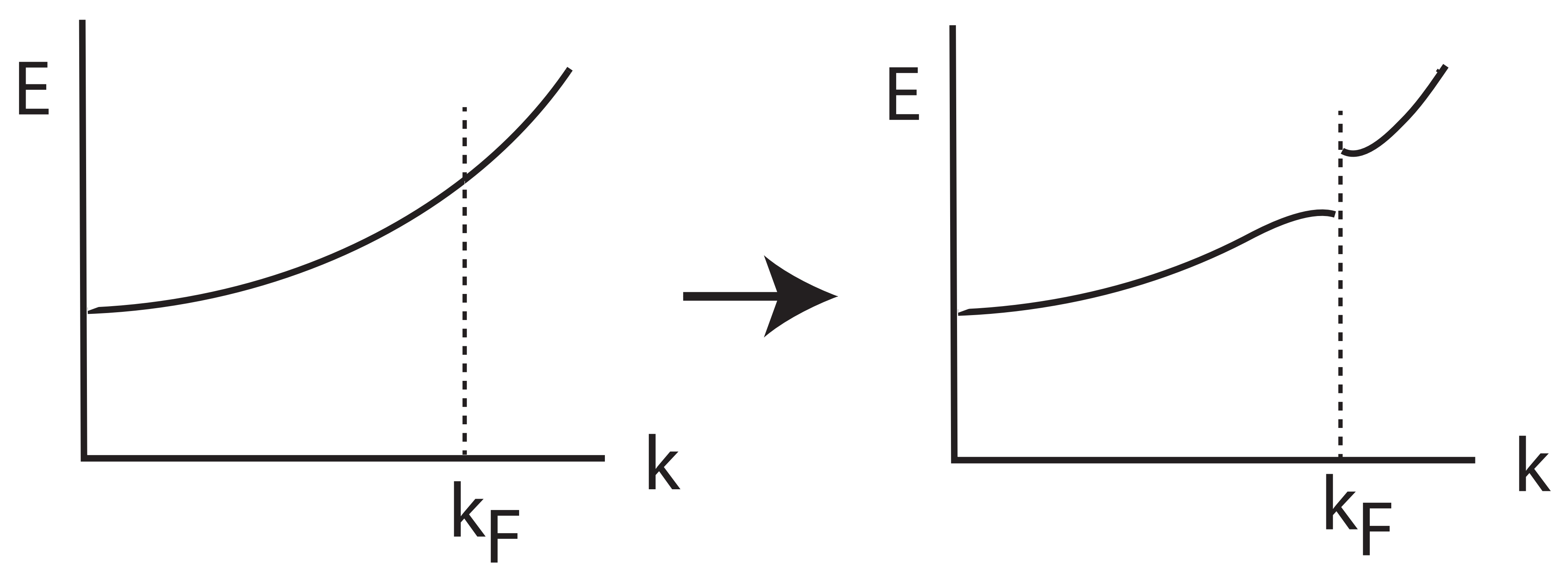
$$\mathscr{L}_2 = -\bar{N}[\gamma\partial - g_0(\sigma' + i\boldsymbol{\tau}\cdot\boldsymbol{\pi}\gamma_5)]N - \frac{(\partial\boldsymbol{\pi})^2}{2} - \frac{(\partial\sigma')^2}{2} - \frac{\mu_0^2}{2}(\pi^2 + \sigma'^2) - \lambda_0\left[\pi^2 + \sigma'^2 - \frac{1}{4f_0^2}\right]^2 - \frac{\mu_0^2}{2f_0}\sigma',$$

"The fact that the σ coupling is responsible for the nucleon mass is a curious property of the model. Unless we can explain all masses, or at least all baryon masses, in a similar way, it is not very satisfactory."

Nambu approached the same set of questions from a completely different direction.

For 2 years, he had been studying the BCS theory of superconductivity.

A property of that theory is the opening of a mass gap in the Fermi sea.



He asked: Why couldn't this be the origin of the nucleon mass ?

Nambu-Jona-Lasinio (1961)

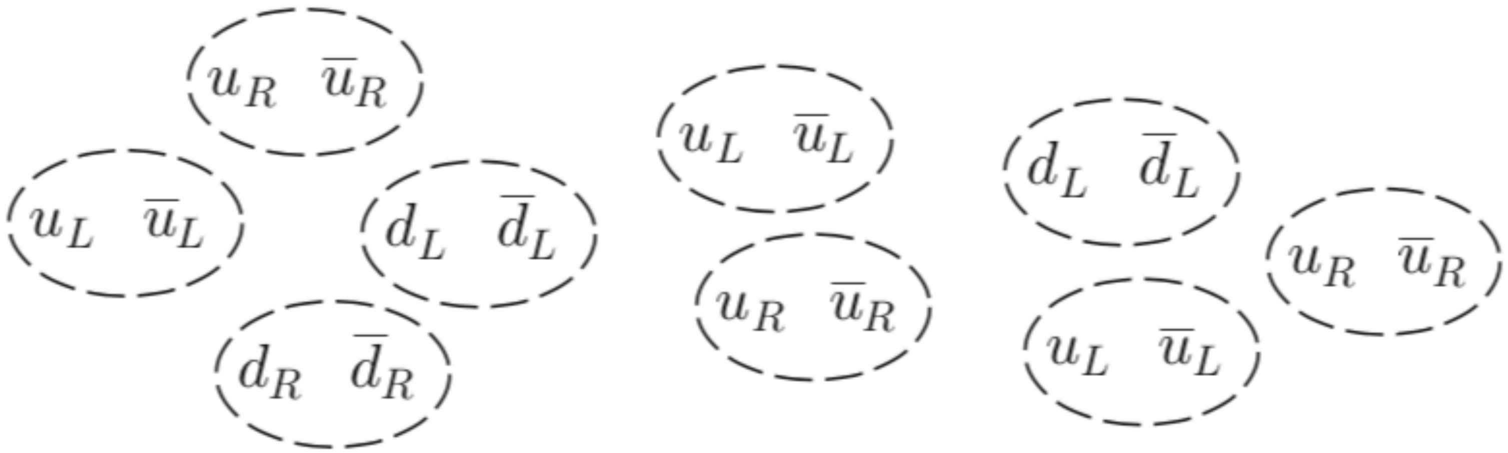
$$E\psi_1 = \sigma\cdot p\psi_1 + m\psi_2,$$
$$E\psi_2 = -\sigma\cdot p\psi_2 + m\psi_1,$$
$$E_p = \pm(p^2+m^2)^{\frac{1}{2}},$$

where ψ_1, ψ_2 are the L and R chirality states of the nucleon.

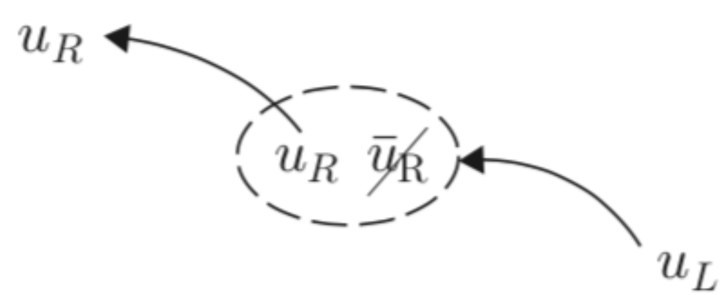
The axial current and the pion naturally appear, with the properties just discussed. A crucial insight is the physical importance of the limit

$$m_\pi^2 \to 0$$

This idea comes with a physical picture of the strong interaction vacuum



and of the nucleon mass generation.



A modern view would replace (p,n) by (u,d) and the ad hoc Nambu-Jona-Lasinio coupling by attractive QCD forces, but otherwise all of correct ingredients are there.

As a student in the 1970's, I was amazed to learn about these insights, which had not, at that time, become part of the canon.

I was swept away by these ideas. Today, perhaps, they are less novel, but still they are an essential part of our understanding of how QCD leads to the observed features of the strong interactions.

Often, we say that there are two stages to understanding the fundamental interactions — discovery or clarification of the phenomena, and then the formulation of the correct equations.

But, actually, Nambu worked in a regime between these two.

Before we can find the equations, we need a physics picture that these equations should represent.

"First, I would like to talk about the influence of Sakata-Taketani philosophy in the immediate postwar period. They were collaborators with Yukawa in creating the meson theory but also advocated and developed a unique philosophy. Taketani often came to see his friend S. Nakamura near our office, and expounded his theory before us. I need not explain here his "three-stages" theory, but we youngsters were overwhelmed by his persuasive elegance."

- Bull. Japan. Phys. Soc. 57, No. 1 (2003)

“According to the “three-stage theory” of [Mitsuo] Taketani, cognition of nature develops spirally through the following three characteristic stages:

The first is the phenomenological stage in which the phenomenon is described as it is.

The second is the substantialistic stage in which it is investigated what structure the object has.

The third is the essentialistic stage in which it is clarified by what interactions and under what laws of motion that object moves.”

Shoichi Sakata, “Course of the development of Yukawa theory”, Shizen (1949) [Suppl. Prog. Th. Phys. 50, 9 (1971)]

Nambu's other great discoveries

- the postulate of vector mesons to explain the repulsive core of the nuclear forces
- the idea of Nambu-Goldstone bosons as an essential product of spontaneous symmetry breaking
- the postulate of a physical color group to account for the statistics of quarks in baryons
- the interpretation of the Veneziano model as a relativistic string

also all belong to this "substantialistic" phase of discovery in physics.

Today, we need this type of insight more than ever.

We have a Standard Model of particle physics that is highly successful and predictive.

But, it is built on sand. More precisely, this model has spontaneous symmetry breaking as an essential feature, but its model of symmetry breaking is the same linear sigma model

$$V(\varphi) = -\mu^2|\varphi|^2 + \lambda(|\varphi|^2)^2$$

that has proven so unsatisfactory in the past.

We have proposed physical pictures to replace this theory ("technicolor", "supersymmetry"), but their predictions have not been borne out.

Before we have a fundamental description, field equations, unification, we need a picture.

This picture will reveal new fundamental forces beyond those of the Standard Model. They are waiting to be discovered.

New experiments are essential. We need to clarify the properties of the Higgs field and search for clues that require structure beyond the linear σ model. This is the crucial role of the Higgs factories such as the ILC.

And, we need the next Nambu to imagine how the properties revealed by these experiments will organize themselves into a new level of understanding.

In the history of physics, we see the patterns of discovery repeated.

At the same time, the new stages of discovery require new and more subtle ingredients.

This is true of Nambu's discovery of the chiral symmetry structure of hadrons.

It will be true again in the coming discovery of the true nature of the Higgs boson.

photo: Spenta Wadia/CERN Courier