Superconductivity at 100: some reflections

A. Zee
Institute for Theoretical Physics
University of California
Santa Barbara, CA

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Poster child of the profound impact of one area of physics on another

Superconductivity (April 8, 1911)-> Electroweak unification

Yang-Mills theory (1954) massless gauge bosons

--- rendered massive

--- confined

--- ???

Ginzburg-Landau (1950), Bardeen-Cooper-Schrieffer (1957)

$$\mathcal{F} = \frac{1}{2m}|(-i\hbar\vec{\nabla} - 2e\vec{A})\phi|^2 + \cdots \to \frac{(2e)^2}{2m}v^2 A^2 + \cdots$$

Energy of constant magnetic field in superconductor scales faster than volume since $\vec{A} = \vec{x} \times \vec{B}$

Meissner-Ochensfeld effect (1933)
=> “Higgs mechanism” (1963-64)

Note: does not depend on BCS as such, but only after BCS, did Nambu and Anderson recognized relevance to relativistic physics

On the spectrum from the Universal to the Specific

--Ginzburg-Landau --BCS -- specific material

Universal versus Specific

Fine balance in theoretical physics

Pitfalls for theoretical physicists working in biophysics
e.g. topology versus “this and that” RNA

Fundamental outlooks differ, but range much narrower within theoretical physics

Even if Higgs particle(s) discovered,
we still don’t have the analog of BCS

Concepts in one area of theoretical physics migrating to another: a glorious history

Some examples

Diffraction: water wave => sound wave, electromagnetic wave, quantum wave

Eigenfrequency: Vibrating string => quantization

Spontaneous symmetry breaking: spin wave in ferromagnet => pion as Nambu-Goldstone boson

Search for the Universal

Fermat: Least time principle
Euler-Lagrange: Action principle

What do we "gain"?
Dirac-Feynman path integral formulation of quantum mechanics offers the most natural path to quantum field theory

The action principle permeates modern theoretical physics

Hilbert almost beat Einstein to the punch!

That Ginzburg-Landau holds the key to the electroweak interaction seems obvious now, but that is in the glare of hindsight, an instance of staircase wit.

Could a bright young guy in 1954, 55, 56, or even 57 have seen the relevance of Meissner and Ginzburg-Landau to the dilemma facing Yang-Mills theory?

(No way!)

What lessons, if any, can we learn?

What does the order parameter have to do with a field?

Quantum fields as highly singular operators.
“Don’t mess with fields!”

Shackles of Feynman diagrams
Students were taught quantum field theory as sums of perturbative diagrams (as late as early 1970s or perhaps even now in some places)

What does free energy have to do with the action of a relativistic theory?

Both functionals of fields (order parameters)

But the way we learn about free energy, all tied up with mysterious concepts like temperature and entropy, would have prevented us from seeing the connection.

Lesson is to look for similar objects from different areas of physics?

What does the London penetration length have to do with the mass of a Yang-Mills gauge boson?

Compton wavelength (1922) $\frac{\hbar}{Mc}$

Conceivably, someone could have seen the connection, but it would have taken a stroke of genius.

As far as I know, nobody suggested anything remotely like that. Even Landau, who straddled condensed matter and particle physics, did not see the connection.

Would non-relativistic conclusions hold in a relativistic context?

In hindsight, it is clear that the addition of time does not change anything essential, but only in hindsight!

Indeed, Higgs' first paper was in response to some confusion on this issue. See later.

The deep concept behind all this --- spontaneous symmetry breaking --- dating back to Heisenberg and ferromagnets, was first recognized as such in this context by Nambu.

My former “boss” (twice over!) Bob Schrieffer (26 in 1957) told me that when he gave his talk at the University of Chicago, the old guys, in particular Wentzel (59 in 1957), gave him a hard time, but Nambu (36 in 1957) the youngster saw the profound implications.

What if ?

Suppose superconductivity had not been discovered. (Perhaps refrigeration technology is particularly poor in this civilization.). What would have happened to electroweak unification.

My contrarian (?) view: not much

I think that with Heisenberg's idea of spontaneous symmetry already fermenting for decades, some theorist would sooner or later ask what would happen in a gauge theory.

In fact, Higgs' first paper (received 27 July 1964) did not mention superconductivity at all, but his second (received 31 August 1964) did, (and was written in "modern language".)

Some history

Higgs' first paper mentioned two confusing papers: one by Klein and Lee showing that Goldstone's theorem could be avoided in a non-relativistic theory because an additional vector n^μ becomes available, and a subsequent paper by Gilbert arguing against Klein and Lee showing that such a vector is absent in relativistic theories.

Higgs pointed out that in gauge theories, gauge fixing introduced this vector.

More history

Anderson's paper (received 8 November 1962) starts the abstract by saying "Schwinger has pointed out that the Yang-Mills vector boson ….. Does not necessarily have zero mass, if …..". He talks about Sakurai's 1961 attempt to use Yang-Mills for the strong interaction. **(Sakurai should have interchanged the strong and the electroweak!)**

Anderson concludes: "…considering the superconducting analog, …the way is now open for a degenerate vacuum theory of the Nambu type without any difficulties involving either zero-mass Yang-Mills gauge bosons or zero-mass Goldstone bosons. These two types of bosons seem capable of 'canceling each other out' and leaving finite mass bosons only."

Transporting the concepts from one physical problem to another

The method of analogy in theoretical physics

A possible example:

The cosmological constant paradox (the most humongous discrepancy between expectation, dogma, and observation in theoretical physics today)

Could it be solved by appealing to the proton decay story as an analogy? (See my talks at Dirac's 80^{th}, Yang's 85^{th}, and Gell-Mann's 80^{th})

I end with an extremely lame concluding remark

The next great idea in particle physics

Where will it come from?