Title: Lessons from the role of non-relativistic causal models in the history of QFT?

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Collection: Indefinite Causal Structure

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Abstract: There are a number of cases in the history of particle physics in which analogies to non-relativistic condensed matter physics models guided the development of new relativistic particle physics models. This heuristic strategy for model construction depended for its success on the causal structure of the non-relativistic models and the fact that this causal structure is not preserved in the relativistic models. Focusing on the case of spontaneous symmetry breaking, the heuristic role of representations of causal structure and time in the non-relativistic models will be examined. I will reflect on whether the use of non-relativistic causal models to construct relativistic quantum field theory models offers methodological lessons for the shift from definite causal structures in pre-general relativistic quantum theories to indefinite causal structures in quantum gravity.

Lessons from the role of non-relativistic causal models in the history of QFT?

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Context

Can we learn lessons from the strategies that were successful in formulating past theories that that might be useful today (e.g., in search for QG)?

Historical example: Analogies to models of superconductivity models guided the construction of the Higgs model

superconductor model : Higgs model ::
QT models with DCS : QG models with ICS

✓ causal structure of the superconductor model plays crucial role

✓ causal structure is partly responsible for the superconductor model being more physically intuitive than Higgs model

✗ (?) analogy between QSM and QFT models, not relationship between successor theories (e.g., GR succeeds SR)

Questions from yesterday

What is the ontology of causal structure?
Or: *What are the possible ontologies of causal structure?*

How does time relate to causality?

Is time just a measure of change or is it fundamental?

Overview

1. Historical example: How analogies to superconductivity guided construction of Higgs model
2. Two different accounts of causal structure
3. Potential lessons for indefinite causal structure

Historical context c.1962

Superconductivity:

- Ginzburg-Landau phenomenological model (1950)
- Bardeen-Cooper-Schrieffer (BCS) dynamical model (1957)

Particle physics:

- QED
- Goldstone's theorem (1961/2)
- Yang-Mills theories with massless bosons

Formal Analogies: Spontaneously Broken Symmetry

Ginzburg-Landau model of superconductivity and the Higgs model of particle physics

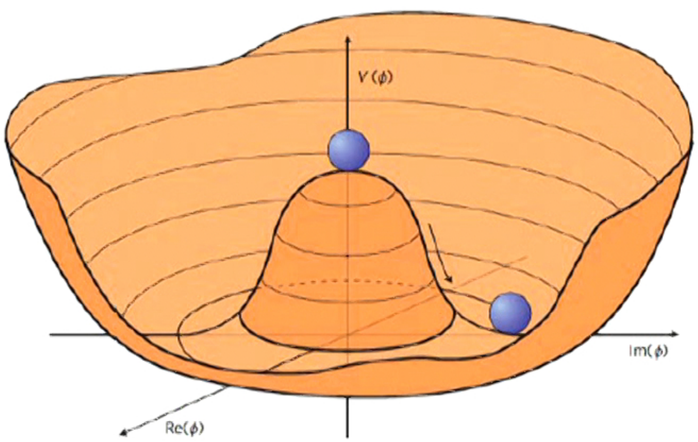

Image credit: John Ellis, CERN

Higgs model V_H

$$\mu^2|\phi(x)|^2 + \lambda|\phi(x)|^4 \qquad (1)$$

G-L model free energy density term

$$a|\psi(\mathbf{x})|^2 + \frac{b}{2}|\psi(\mathbf{x})|^4 \qquad (2)$$

Fraser and Koberinski (2016), "The Higgs mechanism and superconductivity: A case study of formal analogies" SHPMP

Formal Analogies

GL model	**Higgs model**
$U(1)$ broken (global) gauge symmetry group	$SU(2) \times U(1)$ broken (local) gauge symmetry group
(limited-range) photon with effective mass (two transverse components)	massive W, Z bosons
plasmon with massive longitudinal component	massive Higgs boson
free energy density of superconducting state $\mathcal{F}_s$	Lagrangian $\mathcal{L}$
$a\lvert\psi(\mathbf{x})\rvert^2 + \frac{b}{2}\lvert\psi(\mathbf{x})\rvert^4$	$V_H = \mu^2\lvert\phi(x)\rvert^2 + \lambda\lvert\phi(x)\rvert^4$
collective wave function for superconducting electrons $\psi(\mathbf{x})$ as the order parameter	scalar particle field $\phi(x)$ as the order parameter
T	*no analogue*

Significant Physical Disanalogies

- *space* in GL model (NRQM) gets mapped to *spacetime* in Higgs model (RQFT)
- temporal processes (e.g., SSB) in GL model **not** mapped to temporal processes in Higgs model
- causal structure in GL model **not** mapped to causal structure in Higgs model
- modal structure in GL model **not** mapped to modal structure in Higgs model
  - for a given system, superconducting and non-superconducting states can be physically possible
  - for a given system, states which are symmetric and states in which the symmetry is broken are not both physically possible

Causal structure in superconductor models

QSM models of superconductors:

- open systems that can be manipulated from outside
- temperature is an exogenous control variable
- time is a parameter

Manipulability accounts of causation: "causal relationships are relationships that are potentially exploitable for purposes of manipulation and control: very roughly, if C is genuinely a cause of E, then if I can manipulate C in the right way, this should be a way of manipulating or changing E." (Woodward)

(Reference: Woodward (2003), *Making things happen: A theory of causal explanation*)

Causal structure in QFT models (e.g., Higgs)

The analogical mappings do not map the causal (and temporal) process of SSB in the superconductor model to a causal (and temporal) process of SSB in the Higgs model.

Higgs model:

- closed systems possible
- no temperature (or other exogenous control variable)
- background spacetime

Causal structure in QFT models (e.g., Higgs)

Relativistic spacetime structure constrains causal structure in familiar ways

Ex: Microcausality axiom in algebraic QSM vs QFT

Microcausality: Whenever $\Lambda_1, \Lambda_2 \in \mathcal{F}$ and $\Lambda_1 \bowtie \Lambda_2$, every element of $\mathfrak{A}(\Lambda_1)$ commutes with every element of $\mathfrak{A}(\Lambda_2)$

- $\mathcal{F}$: net of finite regions Λ_i
- regions Λ: space or spatial lattice for QSM vs. spacetime for QFT
- **casual disjointness $\bowtie$: $\boldsymbol{\Lambda_1 \cap \Lambda_2 = 0}$ in QSM vs. spacelike separation in QFT**

What explains the success of formal analogies in this case?

- Misconceptions in particle physics c.1962: Gauge bosons massless, SSB accompanied by massless Goldstone bosons. Formal analogy allows possibilities inherent in mathematical formalism of SSB to be appreciated. Easier to construct solid state models.
- Moreover, physical disanalogies actually contributed to heuristic usefulness of the formal analogy (e.g., key features of superconductivity model accessible to experiment).
- Hypothesis: Formal implications of SSB were clearer in solid state physics because there was a clearer intuitive picture of superconductivity than particle physics systems.

Potential lessons for ICS

Goal: To use quantum SWITCH to inform new models for QG

superconductor model : Higgs model ::
QT models with DCS : QG models with ICS

Similarities:

- looking for plausible strategy to develop a new theory (Higgs model and QG)
- QT with DCS is experimentally more accessible than QG
- ICS is less physically intuitive than DCS!
- supermaps are higher-order structure, like SSB
- application of manipulability account of causation in info theoretic/resource theory/control theory approaches to QT (with DCS)
- causal structure constrained by spacetime structure in QFT and (presumably) QG

Potential lessons for ICS

Formal analogy between G-L and Higgs models useful even though it does not map causal structure to causal structure.

Is there a formal analogy between QT models with DCS that would help inform construction of a QG models with ICS?