Gauge theory and the Aharonov-Bohm effect: the view from philosophy

1959 Aharonov and Bohm

1960 Chambers

1988 Brown and Harré, *Philosophical Foundations of Quantum Field Theory*, Weingard and Cao

1992 Zangari (Proceedings of the Biennial Meeting of the Philosophy of Science Association)

Zangari (1992)
"Adding potential to a theory of causation"

Which sequences of events are causal processes?

(Aronson, 1971; Bigelow, Ellis, and Pargetter, late 1980s and early 1990s)

Heathcote, 1989:

- Causality *just is* "*interaction* as defined by a suitable quantum field theory".
- "all causal influences are the result of forces between objects, all such forces are interactions *in the sense of QFT*".

Zangari:

- Yes, we should look at interactions.
- But, if we do that then AB effect gives us some interesting puzzles
  - we have three basic approaches to characterizing the effect
  - we have a variety of different principles we might be antecedently committed to
  - whichever approach you adopt, one or more of these principles will have to be sacrificed

Dominant theme of the AB literature

The three basic approaches to the AB effect

The AB effect is best characterized:

(A) as an interaction between the electrons and the electromagnetic potential

(B) as arising from the influence of the magnetic field on the electrons

(C) in terms of phase factors, holonomies, Wilson loops

Five Principles

- Local action (continuity condition on propagation of causal influence)
  - systems depending on degrees of freedom A(x) and B(y) can be causally connected only if either x-y is not spacelike or x and y are infinitesimally close. (Zangari)
  - If A and B are spatially distant things, then an external influence on A has no immediate effect on B. (Healey)
  - All causes of an event propagate only via continuous causal processes (Lyre et al., 2001)
- Point-like interaction (coupling condition)
  - Interacting entities couple to one another point by point in spacetime (Lyre et al., 2001)
- Separability (property distribution condition)
  - Any physical process occurring in a spacetime region R is supervenient upon an assignment of qualitative intrinsic physical properties at spacetime points in R. (Healey)
- Observability (epistemically motivated condition concerning which theoretical entities can be interpreted as physically real)
  - Gauge invariance (Zangari): "only those mathematical terms that are gauge invariant are considered to be physically interpretable as descriptions of real entities"
- Avoid radical indeterminism
  - (Healey, 1997; Maudlin, 1998; Healey, 1999; on "One True Gauge")

Theme 1: Principled choices

	A (potentials)	B (magnetic field)	C (holonomies...)
Local Action	yes	no	yes
Point-like interaction	yes	no	no
Separability	yes	yes	no
Observability	no	yes	yes
Avoids radical indeterminism?	no	yes	yes

Which sequences of events constitute causal processes? The physical basis of causation is interactions

	A (potentials)	B (magnetic field)	C (holonomies...)
Local Action	yes	no	yes
Point-like interaction	yes	no	no (Nounou, 2003)
Separability	yes	yes	no
Observability	no	yes	yes
Avoids radical indeterminism?	no	yes	yes

Theme 2: Interactions

- Zangari (1992)
  - The physical basis of causal processes is in interactions, involving not forces but potentials
- Liu (1994)
  - The AB effect is an interaction between the potentials and the wave packet, showing that both should be considered physically real.
- Auyang (1995) *How is quantum field theory possible?*
  - Lesson from qfts: Interactions must be expressed in terms of potentials, not forces or field strengths
  - Puzzle: "Many physicists were unhappy about the coupling term because the potential is intrinsically conventional. What is a convention doing in our most fundamental physical terms?"
  - Solution: As the example of the AB effect shows, the potential couples to the phase factor (the other conventional element in physical theories)
  - Conclusion: Certain quantities become physically meaningful only when the system is considered in interaction with another system

Auyang (1995)

"In an interacting system in which the changes of one quantity are coupled to the changes of another, absolute changes of one partner have little significance. When we do measurements, we effectively substitute one partner of the interacting system with our experimental equipment and then discount the equipment. We think that we are measuring something absolute."

But what's really going on, she says, is not the measurement of absolute quantities, but this:

"When the two qualities are coupled, what appear to be conventional in isolation cancel each other and express the dynamics of interacting fields. *Both relational properties and their coupling belong to a single event designated by the same x. Thus the concept of event is enriched."*

Rovelli, (2013), "Why Gauge?" (arXiv:1308.5599v2 [hep-th]

Gauge-dependent quantities are those through which systems couple to one another.

Our focus on gauge-invariant quantities is a historical accident, arising because in some circumstances we can disregard the relational character of what we're doing by means of absolute quantities. But that there are such quantities is contingent on the underlying relational quantities that make measurement possible in the first place.

Gauge interactions describe the world because Nature is described by relative quantities that refer to more than one object. ... Gauge is ubiquitous. It is not unphysical redundancy of our mathematics. It reveals the relational structure of our world.

Message (from thinking about interactions): Stop trying to make the gauge freedom go away. If we want to describe interactions, gauge freedom is exactly the kind of thing we should expect to see showing up in our theories, and gauge quantities are exactly the ones which we should interpret as physically real.

Support: Noether's second theorem

Flips the "Observability" objection to gauge quantities on its head.

But: no specifics about what we are committing to in our ontology, or why we should stop worrying about the indeterminism

Healey (1997)
"Nonlocality and the Aharonov-Bohm effect"

(1) Local Action and Separability (Theme 1)

(2) Which condition the AB effect violates depends on your interpretation of quantum mechanics

(3) The nonlocality of the Aharonov-Bohm effect is analogous in important ways to the nonlocality associated with EPR violations of the Bell inequalities. (Theme 3)

Maudlin (1998) "Discussion: Healey and the AB effect"

Crucial difference: You *can't* appeal to local hidden variables to explain EPR correlations so as to retain Local Action and Separability, but for the AB effect you *can* (via the electromagnetic potential)

"The puzzles about the Aharonov-Bohm effect lie in the interpretation of the quantum formalism, not in the impossibility of providing a local account (in Bell's sense)."

Theme 3:

- Does the nonlocality of the AB effect have the same origin as the nonlocality of EPR violations of the Bell inequalities?
- Is the AB effect a quantum effect?

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Classical analogs of the AB effect?
Healey (2004): No.
Non-integrability is necessary but not sufficient for the AB effect?
Because non-integrability is necessary but not sufficient for non-separability?
Why isn't Weyl's 1918 theory an exact analog?

Theme 4: Generality?

Background theme throughout

Are there AB effect analogs in non-Abelian theories?

If so, is the Abelian case nevertheless misleading when it comes to thinking about the more general case?

Are the features that we are focusing on and worrying about preserved when we move to qfts?

(See esp. Zangari, Leeds, Healey, after Healey's 2007 book....)

Gauge theory and the Aharonov-Bohm effect: the view from philosophy

1992 Zangari "Adding potential to a theory of causation"

1994 Liu "The AB effect and the reality of wave packets"

1995 Auyang *How is quantum field theory possible?*

1997 Healey "Nonlocality and the AB effect"

1998 Maudlin "Discussion: Healey and the AB effect"

1999 Healey (reply to Maudlin)

1999 Leeds "Gauges: Aharonov, Bohm, Yang, Healey"

2001 Healey "On the reality of gauge potentials"

2001 Lyre et al "A versus B!"

2002 Redhead "The interpretation of gauge symmetry"

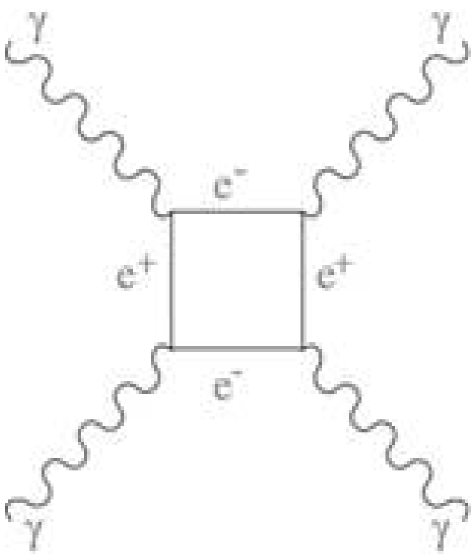
2003 Nounou "A fourth way to the AB effect"

2007 Healey's book

Four themes:

- Principled Choices
- Interactions
- Quantum or classical?
- Generality?

Mark Zangari on presenting his paper on the AB effect at the PSA in 1992



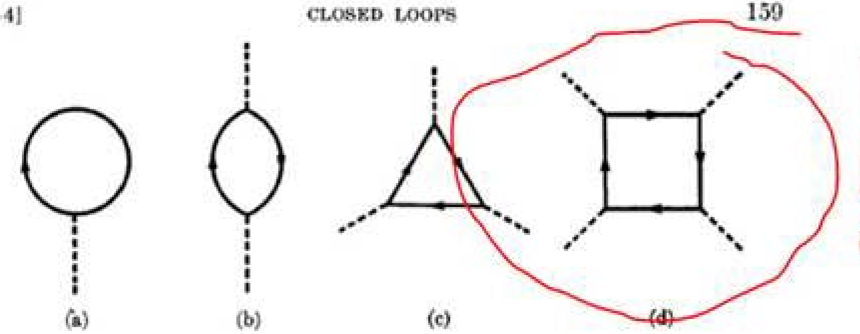


FIG. 8-6. Closed-loop diagrams.

on the classical Hamilton-Jacobi theory and its canonically conjugate variables. A second, and much more relevant, advantage of the new formulation will be discussed in connection with the problem of divergences in Chapters 9 and 10.

The graphical representation of the covariant perturbation calculation has proved not only an aid in computation but also a powerful tool in the investigation of general problems. An example will be found in the next section, where Furry's theorem is proved. This theorem is much more difficult to prove in the older formalism.

8-4 Closed loops. There are a number of important features connected with the occurrence of closed loops in diagrams. We want to discuss them in this section. A typical closed loop was shown in the last drawing of Fig. 8-1. Closed loop diagrams with one to four corners in the loop are shown in Fig. 8-6.

A closed loop is an electron path which is closed in itself and therefore does not contain free electron functions, but only electron propagation func-