Long Range Interactions and Structure of Charge Classes in Quantum Field Theory

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Persistent interactions

- "Exotic infrared representations of interacting systems"
  D. Buchholz and S. Doplicher (1984)
- "On Noether's theorem in quantum field theory"
  D. Buchholz, S. Doplicher and **R. Longo** (1986)
- "Nuclear maps and modular structures. 1. General properties"
  D. Buchholz, C. D'Antoni and **R. Longo** (1990)
- "Nuclear maps and modular structures. 2. Applications to quantum field theory"
  D. Buchholz, C. D'Antoni and **R. Longo** (1990)
- "A new look at Goldstone's theorem"
  D. Buchholz, S. Doplicher, **R. Longo** and J. E. Roberts (1992)
- "Extensions of automorphisms and gauge symmetries"
  D. Buchholz, S. Doplicher, **R. Longo** and J. E. Roberts (1993)
- "A model for charges of electromagnetic type"
  D. Buchholz, S. Doplicher, G. Morchio, J. E. Roberts and F. Strocchi
- "Graded KMS functionals and the breakdown of supersymmetry"
  D. Buchholz and **R. Longo** (1999)
- "Quantum delocalization of the electric charge"
  D. Buchholz, S. Doplicher, G. Morchio, J. E. Roberts and F. Strocchi (2001)
- "Asymptotic abelianness and braided tensor C*-categories"
  D. Buchholz, S. Doplicher, G. Morchio, J. E. Roberts and F. Strocchi (2007)
- "Nuclearity and thermal states in conformal field theory"
  D. Buchholz, C. D'Antoni and **R. Longo** (2007)
- "New light on infrared problems: Sectors, statistics, symmetries and spectrum"
  D. Buchholz and J.E. Roberts (2013) arXiv:1304.2794 (dedicated to **R. Longo**)

Notorious problems

Relativistic QFTs in $(\mathbb{R}^4, g)$ describing long range forces (QED) exhibit

- abundance of sectors with given total charge ~~superposition~~
- massless "infrared clouds" ~~particles~~
- spontaneous breakdown of Lorentz symmetry ~~spin~~
- infraparticles ~~mass~~
- no "localizable" charged fields ~~statistics~~

Theory in conflict with experiment? Workaround:

- *ad hoc* selection of sectors (choice of gauge)
- introduction of fictitious (photon) masses
- inclusive processes (splitting into "soft" and "hard" contributions)

Conceptually unsatisfactory; many unanswered questions!

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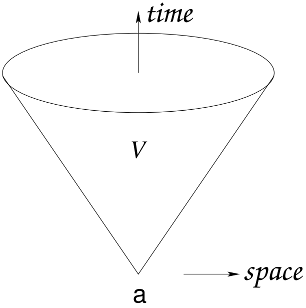
Ingredients for solution

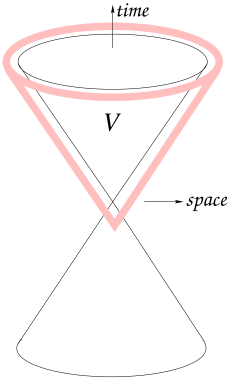
(1) Arrow of time



Experiments take place in future lightcones V over some spacetime point a.
Impossible to make up for missed measurements in the past of a.

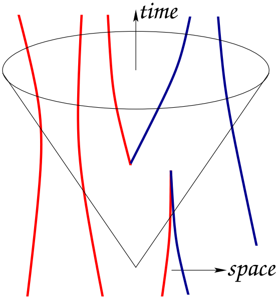
Theory only needs to describe and explain data taken in lightcones V.

(2) Huygens Principle



Outgoing radiation/massless particles created in the past of apex *a* escape observations in V (propagate with velocity of light c); as a consequence infrared clouds cannot be discriminated in V

(3) Nature of charges



Total charge can be determined in any V (speed less than c)

Framework

Observables of a (given) QFT

- generate a unital C*–algebra $\mathcal{A} \subset \mathcal{B}(\mathcal{H})$
- are localized in space–time regions $\mathcal{O}$ (Heisenberg picture)

$$\mathcal{O} \mapsto \mathcal{A}(\mathcal{O}) \subset \mathcal{A}$$

- comply with Einstein causality (locality)

$$[\mathcal{A}(\mathcal{O}_1), \mathcal{A}(\mathcal{O}_2)] = 0 \ \text{ if } \ \mathcal{O}_1 \times \mathcal{O}_2 \ \text{ (spacelike separation)}$$

- are covariant under automorphic action α of the Poincaré group

$$\alpha_\lambda \, \mathcal{A}(\mathcal{O}) = \mathcal{A}(\lambda\mathcal{O}) \,, \quad \lambda \in \mathcal{P}_+^\uparrow \doteq \mathbb{R}^4 \rtimes \mathcal{L}_+^\uparrow$$

- admit vacuum state $\Omega \in \mathcal{H}$ and unitary representation U of $\mathcal{P}_+^\uparrow$

$$U(\lambda) A \Omega = \alpha_\lambda(A) \Omega \,, \quad \lambda \in \mathcal{P}_+^\uparrow, \ A \in \mathcal{A}$$

spectrum condition, uniqueness of vacuum, Reeh–Schlieder property . . .

Basic facts

In the following V is kept fixed

Fact [Longo 1979]: Let $\mathcal{R}(V) = \mathcal{A}(V)''$. There are the alternatives

(a) $\mathcal{R}(V) = \mathcal{B}(\mathcal{H})$

(b) $\mathcal{R}(V)$ is a factor of type III_1 (with separable pre–dual)

Examples

(a) theories of massive particles (mass gap)
$\Rightarrow$ no loss of information by delayed measurements

(b) theories including massless particles
$\Rightarrow$ incomplete information due to outgoing radiation from the past

Physical operations in V $\hat{=}$ group of inner automorphisms $\mathrm{In}\,\mathcal{A}(V)$

Fact [Kadison 1957]: In case (a) $\mathrm{In}\,\mathcal{A}(V)$ acts transitively (adjoint action) on pure normal states.

$\Rightarrow$ Concept of superselection sector of physical state space

Fact [Connes + Størmer 1987]: In case (b) $\mathrm{In}\,\mathcal{A}(V)$ acts almost transitively (adjoint action) on normal states.

$\Rightarrow$ Concept of charge classes

Focus on theories with massless particles, *i.e.* on case (b)

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Charge classes

Definitions Let φ be a state on $\mathcal{A}(V)$

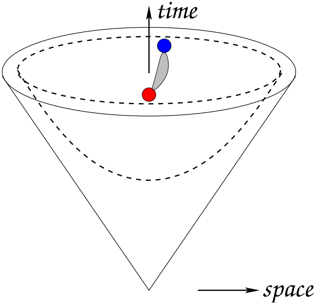
- φ is said to be *elemental* if it is of type III_1 (GNS)
- *charge class* of such φ is the norm closure of $\varphi \circ \mathrm{In}\,\mathcal{A}(V)$

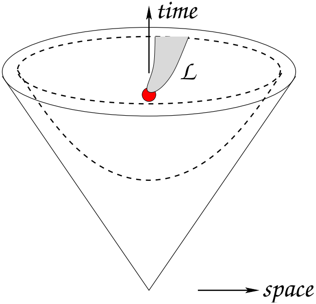
Example: vacuum $\omega = \langle \Omega \cdot \Omega \rangle \upharpoonright \mathcal{A}(V)$; charge class $\hat{=}$ neutral states
(unites abundance of sectors differing only by “infrared clouds”)

Question Other charge classes of interest? Physics!

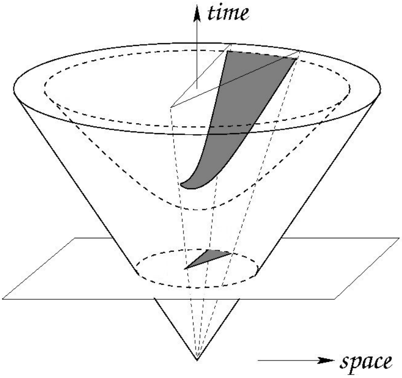
Passage to charge classes of interest can be accomplished by limits of local operations on some Cauchy surface (time–shell) in V:

Create a pair of opposite charges and shift unwanted charge to spacelike infinity (lightlike boundary of V) within a given *hypercone* $\mathcal{L}$





hypercone $\equiv$ causal completion of a pointed convex hyperbolic cone formed by geodesics on some time–shell



(Beltrami–Klein model: hyperbolic cone $\hat{=}$ truncated Euclidean cone)

Formalization: Given $\mathcal{L}$ there is a sequence $\{\mathrm{Ad}\, W_n \in \mathrm{In}\, \mathcal{A}(\mathcal{L})\}_{n\in\mathbb{N}}$

$$\sigma_{\mathcal{L}}(A) \doteq \lim_n \mathrm{Ad}\, W_n\,(A) \;\text{ exists, }\; A \in \mathcal{A}(V)$$

(convergence in strong operator topology) and $\omega \circ \sigma_{\mathcal{L}}$ describes elemental state in target charge class

Properties:

(a) $\sigma_{\mathcal{L}} : \mathcal{A}(V) \to \mathcal{R}(V)$ *morphism*

(b) $\sigma_{\mathcal{L}} \upharpoonright \mathcal{A}(\mathcal{L}^c) = \iota$ (identity map) if $\mathcal{L} \times \mathcal{L}^c$

(c) $\sigma_{\mathcal{L}}\,(\mathcal{A}(\mathcal{L}^b))'' \subseteq \mathcal{R}(\mathcal{L}^b)$ if $\mathcal{L} \subseteq \mathcal{L}^b$ (equality: $\sigma_{\mathcal{L}}$ *simple morphism*)

(d) for given charge class and any $\mathcal{L}_1, \mathcal{L}_2$ there are corresponding morphisms $\sigma_{\mathcal{L}_1} \simeq \sigma_{\mathcal{L}_2}$ with intertwiners $W \in \mathcal{R}(V)$

Remarks: (a) to (c) express the fact that charges can be created in any $\mathcal{L}$, whereas assumption (d) says that the resulting infrared clouds cannot be discriminated in V.

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Analysis

Familiar input: Haag–duality rephrased for lightcones [Camassa]

Complete results for morphisms describing **simple** charge classes

- can be "composed", $\sigma_1, \sigma_2 \to \sigma_1 \bullet \sigma_2 \simeq \sigma_{12}$ (addition of charge content)
- can be "inverted", $\sigma \to \overline{\sigma}$ and $\sigma \bullet \overline{\sigma} = \overline{\sigma} \bullet \sigma = \iota$ (charge conjugation)
- can be "exchanged", $\sigma_1 \bullet \sigma_2 \simeq \sigma_2 \bullet \sigma_1$, intertwiner $W(\sigma_1, \sigma_2) \in \mathcal{R}(V)$; if $\sigma_1 \simeq \sigma_2$ and $\mathcal{L}_1 \times \mathcal{L}_2$ then $W(\sigma_1, \sigma_2) \in \{\pm 1\}$ (Bose/Fermi statistics)
- $\sigma, \overline{\sigma}$ obey same statistics
- $\{$simple morphisms$\} / \simeq$ form abelian group, dual of compact abelian group (global gauge group)
- properties do not depend on chosen lightcone V

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Spacetime symmetries: V admits only semigroup action of $\mathcal{S}_+^\uparrow \doteq \overline{V}_+ \rtimes \mathcal{L}_+^\uparrow$

Definition A simple morphism σ is said to be *covariant* if there exists a family of "transported" morphisms ${}^\lambda\sigma \simeq \sigma$ such that

$$ {}^\lambda\sigma \circ \alpha_\lambda = \alpha_\lambda \circ \sigma \, , \quad \lambda \in \mathcal{S}_+^\uparrow $$

and $\alpha_\mu(W_\lambda) \in \mathcal{R}(V)$ are intertwiners between ${}^{\mu\lambda}\sigma$ and ${}^\mu\sigma$, $\mu, \lambda \in \mathcal{S}_+^\uparrow$

Results Covariant simple morphisms σ

- are stable under composition and conjugation
- determine unique unitary representations U_σ of (the covering of) the full Poincaré group $\tilde{\mathcal{P}}_+^\uparrow = \mathbb{R}^4 \rtimes \tilde{\mathcal{L}}_+^\uparrow$ such that

$$ U_\sigma(\tilde{\lambda})\sigma(A)U_\sigma(\tilde{\lambda})^{-1} = \sigma(\alpha_\lambda(A)) \, , \quad \tilde{\lambda} \in \widetilde{\mathcal{S}}_+^\uparrow \, , \; A \in \mathcal{A}(V) $$

- comply with relativistic spectrum condition, $\operatorname{sp} U_\sigma \upharpoonright \mathbb{R}^4 \subset \overline{V}_+$
- describe states with fluctuating energy content

Covariant charge classes have all properties expected from physics!

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Summary

- There is progress in understanding the general structure of physical states in QFTs with long range forces (simple charges)
- Origin of infrared difficulties can be traced back to unreasonable idealization of observations covering all of Minkowski space
- Restriction to observables in a lightcone V amounts to a meaningful geometric (Lorentz invariant) infrared cutoff
- Pertinent algebras of observables $\mathcal{A}(V)$ are highly reducible (due to loss of information about radiation created in the past)
- Information obtainable in V suffices to determine sharply the charges, their statistics and the underlying global gauge group
- Information also fixes representations U_V of the Poincaré group indicating the (fluctuating) energy–momentum content in V

Conjecture: Infraparticle problem (failure of Wigner particle concept in Minkowski space) disappears in the representations U_V