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Cluster Decomposition and Two Senses of Isolability

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The cluster decomposition principle captures the fact that the long-run statistics of experimental outcomes in our laboratories do not depend on events in distant regions of the universe.

The principle is typically formulated as a statistical independence condition either on VEVs of field operators or S-matrix elements.

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Cluster Decomposition and Two Senses of Isolability

RESEARCH

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ABSTRACT

In the framework of quantum field theory, one finds multiple load-bearing locality and causality conditions. One of the most important is the cluster decomposition principle, which requires that scattering experiments conducted at large spatial separation have statistically independent results. The principle grounds a number of features of quantum field theory, especially the structure of scattering theory. However, the statistical independence required by cluster decomposition is in tension with the long-range correlations characteristic of entangled states. In this paper, we argue that cluster decomposition is best stated as a condition on the dynamics of a quantum field theory, not directly as a statistical independence condition. This redefinition avoids the tension with entanglement while better capturing the physical significance of cluster decomposition and the role it plays in the structure of quantum field theory.

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As a condition on VEVs, cluster decomposition requires that if $\{x_i\}$ and $\{y_i\}$ are sets of spacetime points, and all of the points $\{x_i\}$ are translated an arbitrarily large spacelike distance away from all of the points $\{y_i\}$, then the VEV

$$\langle\Omega\,|\,\varphi(x_1)\cdots\varphi(x_n)\,\varphi(y_1)\cdots\varphi(y_m)\,|\,\Omega\rangle$$

factorizes into the product

$$\langle\Omega\,|\,\varphi(x_1)\cdots\varphi(x_n)\,|\,\Omega\rangle\;\langle\Omega\,|\,\varphi(y_1)\cdots\varphi(y_m)\,|\,\Omega\rangle$$

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As a condition on S-matrix elements, cluster decomposition requires that two scattering processes $\alpha \to \alpha'$ and $\beta \to \beta'$ be statistically independent when one is translated an arbitrarily large spacelike distance from the other.

This translates into the requirement that the scattering amplitude for the total process

$$\langle \alpha', \beta' \,|\, S \,|\, \alpha, \beta \rangle$$

factorizes into the product

$$\langle \alpha' \,|\, S \,|\, \alpha \rangle \; \langle \beta' \,|\, S \,|\, \beta' \rangle$$

as the “cluster” of particles β is translated an arbitrarily large spacelike distance away from the “cluster” of particles α.

We argue for a precise articulation of the content of the cluster decomposition principle which:

- Unifies the diverse motivations for adopting the principle
- Clarifies its connection to other locality and causality conditions used in QFT
- Resolves a conceptual tension in standard statements of the principle

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VEVs and S-matrix elements are functions of both operators *and* states, and whether the statistical independence is satisfied will depend on the nature of the vacuum state in which one calculates VEVs or which basis of in and out states one uses to define the S-matrix.

Scattering processes involving entangled states will not factorize at large spacelike separation, which entails that an S-matrix defined using a basis of entangled states will not satisfy cluster decomposition.

The reasoning underlying all of the motivations offered for CD is ultimately aimed as ensuring agents' ability to isolate subsystems.

We argue that stating cluster decomposition as a statistical independence condition conflates two senses in which one could isolate a subsystem, and that this conflation is responsible for the incompatibility with entanglement.

This tension can be resolved by redefining cluster decomposition as a condition purely on the dynamics of a quantum field theory.

On the revised understanding of the content of the principle that we advocate for, cluster decomposition entails a particular kind of statistical independence, but this is a downstream consequence of the principle and not an expression of the content of the principle itself.