Title: Quantum information and the algebraic structure of quantum gravity

Date: May 13, 2015 11:50 AM

URL: http://pirsa.org/15050088

Abstract: Remote talk by teleconference

Perimeter 051315.pdf (page 1 of 29)

Quantum Information and the Algebraic Structure of Quantum Gravity

Steven B. Giddings

U.C. Santa Barbara

Based in part on:

arXiv: 1503.08207
WIP w/ Will Donnelly

Information Theoretic Foundations for Physics
Perimeter Institute May 13, 2015

Perimeter 051315.pdf (page 4 of 29)

Which to trust?

QM Poincaré/Diff invc.	well tested; hard to modify
Locality	hard to formulate in a thy of quantum gravity

Perimeter 051315.pdf (page 5 of 29)

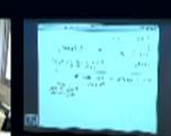
Which to trust?

QM
Poincaré/Diff invc. — well tested; hard to modify

Locality — hard to formulate in a thy of quantum gravity

Quantum mechanics ⇝ Hilbert space $\mathcal{H}$

Information — conservation
sharing (entanglement)
exchange/transfer



The nature of this localization structure, and its relation to usual locality, appears a key question in quantum gravity.

How to provide ?

Classic example: $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$

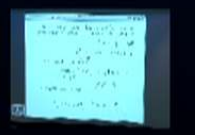
can entangle, transfer info.

More generally, "locally finite" systems:
(e.g. lattice)

$\mathcal{H} = \bigotimes_i \mathcal{H}_i$

... tensor factor structure

What we need in quantum gravity ?



The nature of this localization structure, and its relation to usual locality, appears a key question in quantum gravity.

How to provide ?

Classic example: $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$

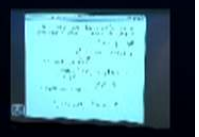
can entangle, transfer info.

More generally, "locally finite" systems:
(e.g. lattice)

$\mathcal{H} = \bigotimes_i \mathcal{H}_i$

... tensor factor structure

What we need in quantum gravity ?

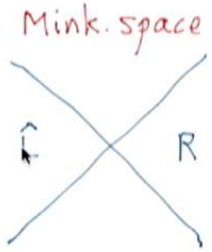


But: we expect a correspondence principle:

Quantum gravity $\xrightarrow[\text{"weak fields"}]{}$ Local Quantum Field Theory (LQFT)

LQFT doesn't have tensor factorized $\mathcal{H}$ – for two reasons!

1. Long-range gauge fields (will return to)
2. Type III property: ∞ entanglement *



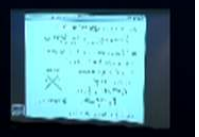
e.g. Rindler – left & right

$$|0\rangle_M \sim \prod_\omega \exp\left\{ z(\omega)\, \hat{b}^\dagger_\omega b^\dagger_\omega \right\} |\hat{0}\rangle |0\rangle$$

$$\sim \prod_{i=1}^{\infty} \left(\frac{|\hat{0}\rangle|0\rangle + |\hat{1}\rangle|1\rangle}{\sqrt{2}} \right)_i$$

(qubit approximation)

* Unless regulate: break symmetry of theory

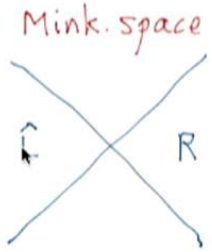


But: we expect a correspondence principle:

Quantum gravity $\xrightarrow[\text{"weak fields"}]{}$ Local Quantum Field Theory (LQFT)

LQFT doesn't have tensor factorized $\mathcal{H}$ – for two reasons!

1. Long-range gauge fields (will return to)
2. Type III property: ∞ entanglement *



e.g. Rindler – left & right

$$|0\rangle_M \sim \prod_\omega \exp\left\{ z(\omega)\, \hat{b}^\dagger_\omega b^\dagger_\omega \right\} |\hat{0}\rangle |0\rangle$$

$$\sim \prod_{i=1}^{\infty} \left(\frac{|\hat{0}\rangle|0\rangle + |\hat{1}\rangle|1\rangle}{\sqrt{2}} \right)_i$$

(qubit approximation)

* Unless regulate: break symmetry of theory

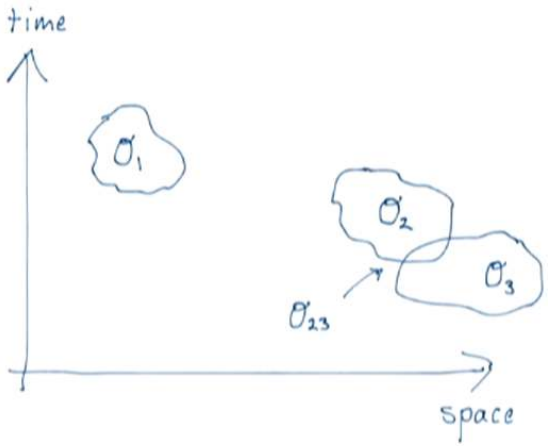
Handle the latter by working w/ algebra of observables.

Localization ↔ Subalgebras

$[A(\mathcal{O}_1), A(\mathcal{O}_2)] = 0$

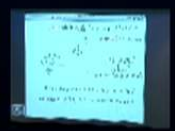
↑ ↑
subalgebras

(for $\mathcal{O}_1, \mathcal{O}_2$ spacelike separated)



"Net" of subalgebras; ⇝ reconstructs spacetime manifold

Basic approach of Algebraic QFT - see e.g. Haag, Local Quantum Physics



QED

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^2 - |D_\mu \phi|^2 - m^2 |\phi|^2 \quad ; \quad D_\mu = \partial_\mu - ig A_\mu$$

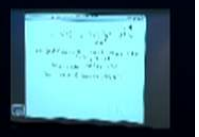
ϕ: scalar

with $g = 0$, a basic observable is $\phi(x)$. Creates (or destroys) particle.

How to generalize?

$$\phi(x) \longrightarrow e^{-ig\Lambda(x)} \phi(x) \quad : \quad \text{not gauge invariant.}$$

$\longleftrightarrow$ "an electron is inseparable from its electric field"



QED

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^2 - |D_\mu \phi|^2 - m^2 |\phi|^2 \quad ; \quad D_\mu = \partial_\mu - ig A_\mu$$

(ϕ: scalar)

With $g = 0$, a basic observable is $\phi(x)$. Creates (or destroys) particle.

How to generalize?

$\phi(x) \to e^{-ig\Lambda(x)} \phi(x)$: not gauge invariant.

$\leftrightarrow$ "an electron is inseparable from its electric field"

but, this can have different configurations = "dressings"

"Simple" example: Faraday (or Wilson) line (Dirac):

$$\Phi_{W_z}(0) = \phi(0)\, e^{ig\int_0^\infty dz\, A_z} \quad :$$

gauge invt.

Indeed, $[E_z(\vec{x},0), \Phi_{W_z}(0)] \propto q\, d^2(x_\perp)\, \Theta(z)\, \Phi_{W_z}(0)$

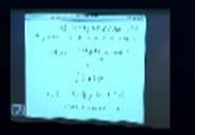
Unnatural/unstable field config. Make symmetric : average $\frac{1}{4\pi}\int d\Omega$

$$\rightarrow \Phi_D(0) = \phi(0)\, \underbrace{e^{iq\int d^3x\, \frac{x^i}{x^3} A_i(0,\vec{x})}}_{V_D(0)}$$

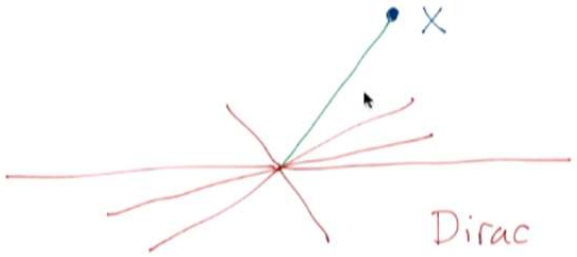
Dirac dressing

Now, $[E^i(x), \Phi_D(0)] \sim -\frac{q}{4\pi}\frac{x^i}{x^3}\Phi_D(0)$ ... Coulomb.

But: state of motion of particle ?



A more general dressing (see, e.g. Bagan, Lavelle, McMullan :)



$(-T, \vec{x}_T)$

$$\Phi_{WL}(x) \sim V_D(-T, \vec{x}_T)\, e^{ig \int_{\text{worldline}} dx^\mu A_\mu}\, \phi(x)$$

$\rightsquigarrow$ e.g., boosted Coulomb field.

What are the consequences for the algebra?

Gravity (in preparation, w/ Donnelly)

$$\mathcal{L} = \frac{2}{\kappa^2} R - \frac{1}{2}(\nabla\phi)^2 - \frac{1}{2} m^2 \phi^2$$

Gauge inv.: $x^\mu \to x^\mu + \xi^\mu$

$\phi(x)$: not gauge invariant

"an electron is inseparable from its gravitational field"

study in linearized theory: $g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$

$$\delta h_{\mu\nu} = -\partial_\mu \xi_\nu - \partial_\nu \xi_\mu$$

Consider, e.g., $\Phi(x) = \phi\left(x^\mu + V^\mu[h_{\lambda\sigma}]\right)$

↑ "Dressing"

Gravity (in preparation, w/ Donnelly)

$$\mathcal{L} = \frac{2}{\kappa^2} R - \frac{1}{2}(\nabla\phi)^2 - \frac{1}{2} m^2 \phi^2$$

Gauge inv.: $x^\mu \to x^\mu + \kappa \xi^\mu$

$\phi(x)$: not gauge invariant

"an electron is inseparable from its gravitational field"

study in linearized theory: $g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$

$$\delta h_{\mu\nu} = -\partial_\mu \xi_\nu - \partial_\nu \xi_\mu$$

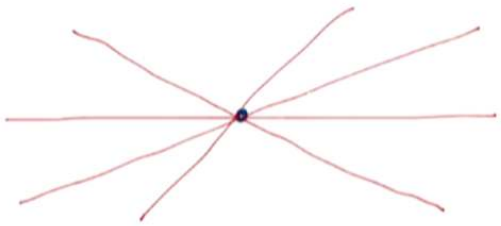
Consider, e.g., $\Phi(x) = \phi\left(x^\mu + V^\mu[h_{\alpha\beta}]\right)$

↕ "Dressing"

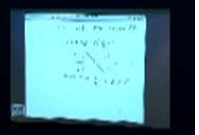
Perimeter 051315.pdf (page 20 of 29)

Make symmetric: average $\frac{1}{4\pi}\int d\Omega$ $\rightsquigarrow$

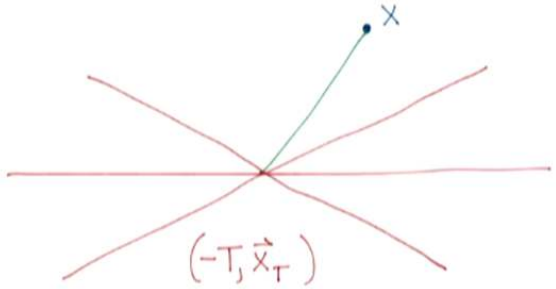
$$V_c^\mu = \frac{1}{4\pi}\int d^3x \frac{1}{r}\Gamma^\mu_{\alpha\beta}\hat{r}^\alpha\hat{r}^\beta + \text{s.t.}$$

$\rightsquigarrow$ 

$[h_{\mu\nu}(x), \Phi_c] \sim h_{\mu\nu}(x)$ linearized Schwarzschild



More general, accounting for state of motion:



$$\Phi_{WL}(x^\mu) = \phi(x^\mu + V_C^\mu + V_{WL}^\mu)$$

$$V_{WL}^\mu \sim \int dx^\lambda x^\sigma \Gamma^\mu_{\lambda\sigma}$$

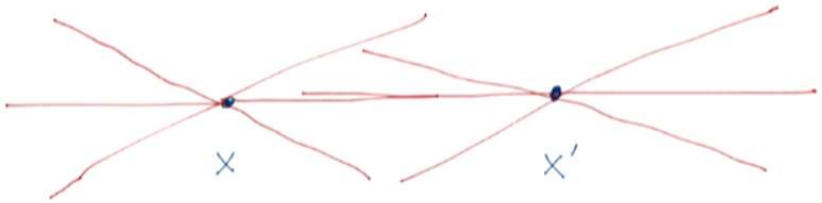
$\rightsquigarrow$ e.g. boosted Schwarzschild, etc.

What are the consequences for the algebra?

$$[\Phi_{W_-z}(x), \Phi_{W_z}(x')] = 0.$$

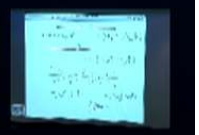
(Though: also nonlin...)

$$[\Phi_{W_z}(x), \dot{\Phi}_{W_z}(x')] \neq 0.$$



$$[\Phi_C(x), \dot{\Phi}_C(x')] \neq 0 \qquad [\Phi_{WL}(x), \dot{\Phi}_{WL}(x')] \neq 0$$

$$\sim \frac{G E_1 E_2}{|\vec{x} - \vec{x}'|}$$



Perimeter 051315.pdf (page 23 of 29)

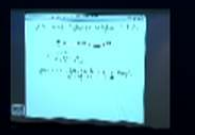
No local subalgebras in gravity? (contrast QED)

can't end

no screening in grav.

(except: $\Lambda > 0$ ...)

Appears to represent irreducible nonlocality in quantum gravity.



Perimeter 051315.pdf (page 24 of 29)

No local subalgebras in gravity? (contrast QED)

can't end

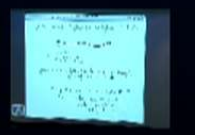
no screening in grav.

(except: $\Lambda > 0$ ...)

Appears to represent irreducible nonlocality in quantum gravity.

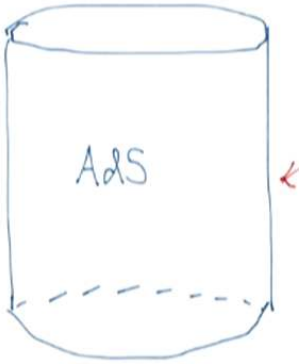
$\Rightarrow$ no obvious def. of local subsystem;

challenge to sharp definitions of
- information flow
- entanglement



Further comments, cont'd:

2) Possible approach to AdS/CFT, if that can be used to define quantum gravity in AdS:

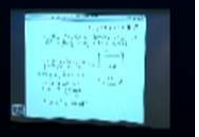


explore algebraic structure of boundary theory

note: boundary subalg. struct.

what ~subalg. struct. associated w/ ~bulk locality?

"decoding the hologram"



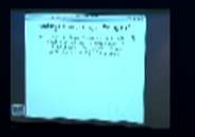
More generally, a question, and a suggestion:

Q: How does approximate locality (approx. subalg. structure) emerge from the more basic quantum theory, and in what sense is it approximate? (Refine locality bound disc.)

Perimeter 051315.pdf (page 27 of 29)

More generally, a question, and a suggestion:

Q: How does approximate locality (approx. subalg. structure) emerge from the more basic quantum theory, and in what sense is it approximate? (Refine locality bound disc.)



Perimeter 051315.pdf (page 28 of 29)

A question, and a suggestion:

Q: How does approximate locality (approx. subalg. structure) emerge from the more basic quantum theory, and in what sense is it approximate? (Refine locality bound disc.)

S: The failure of exact locality underlies the info. transfer from BHs necessary for unitarization.

Possible effective description: (w.r.t. semiclass. geom.)
"Nonviolent nonlocality"
1108.2015
1201.1037
1211.7070 ...

Possible observable signatures at EHT?
1406.7001

Conclusion

- Reasonable expectation:

  quantum gravity ⊂ quantum mechanics

- For physics: want "localization"/subsystem structure
  - tensor factors: problematic in LQFT
  - focus on algebra/subalgebras of observables
- Long range fields: added challenge
  - local subalgebras in QED
  - gravity: obstruction to local subalgebras
- This nonlocality of the algebra is plausibly an important element of the structure of the quantum theory
- Part of story of black hole unitarization?