Homological Toolkit For the Quantum Mechanic
Part II

<u>Recap</u>: ρ_P a multipartite density state; we motivated:

$$\chi_{\alpha,q,r}(\rho_P) = \sum_{\emptyset \subseteq T \subseteq P} (-1)^{|T|} \dim(\mathcal{H}_T)^{\alpha}\, \mathrm{Tr}[\rho_T^{\,q}]^{r}$$

$$\begin{tikzcd}
 & \chi_{\alpha,q,r}(\rho_P) \arrow[dl, "\frac{d}{dq}\big|_{q=1}"'] \arrow[dr, "q\to 0"] & \\
\text{Mutual Inf.} & & \sum_{\emptyset \subseteq T \subseteq P} (-1)^{|T|} \dim(\mathcal{H}_T)^{\alpha}\, \mathrm{rank}(\rho_T)^{r}
\end{tikzcd}$$

$\in \mathbb{Z}$ $\quad (\alpha, r \in \mathbb{Z})$

$\Rightarrow$ is $\dim(\mathcal{H}_T)^{\alpha}\,\mathrm{rank}(\rho_T)^{r}$ the dimension of some vector space?

<u>Thm</u>:

A state $\psi \in \mathcal{H}_A \otimes \mathcal{H}_B$ is factorizable $\Longleftrightarrow$ $\exists$ (For $X = A, B$)

- Left $B\mathcal{H}_X$-modules M_X
- Distinguished points $m_X \in M_X$
- Equivariant maps $\mu_X : M_X \longrightarrow \mathcal{H}_A \otimes \mathcal{H}_B$

s.t.

- $B\mathcal{H}_X \cdot m_X = M_X$ (Cyclic)
- $\mu_X(m_X) = \psi$
- $0 \longrightarrow \mathbb{C} \xrightarrow{\lambda \mapsto (\lambda m_A, \lambda m_B)} M_A \times M_B \xrightarrow{d^0 = pr_A^{*}\mu_A - pr_B^{*}\mu_B} \mathcal{H}_A \otimes \mathcal{H}_B = \mathcal{M}$

  is exact $\left(\operatorname{Ker} d^0 = \mathrm{Span}_{\mathbb{C}}(m_A, m_B)\right)$.

$$H^0(\mathcal{M}) = 0$$

Thus, given $\Psi \in \mathcal{H}_x \otimes \mathcal{H}_B$ we want to find (M_x, m_x, Φ_x) w/ Smallest Cohomology

The GNS-module (Gelfand - Naimark - Segal)

Quasi - Dfs:

- A C^*-algebra is a $\overset{\mathbb{C}-}{\vee}$ V.S. A w/
  - Norm $\|-\|$
  - $m: A \times A \longrightarrow A$ associative mult.
  - $*: A \longrightarrow A$ an anti-linear involution

S.t.

- A is complete
- $*$ plays nicely w/ m
- $\|x^* x\| = \|x\|^2$ (C^*-cond$^{=}$)

Ex: $B\mathcal{H}$, $C^0(X)$ etc. commutative $\prod_{i=1}^{L} M_{n_i}\mathbb{C}$ All F.d. C^*-algs $\cong$ to this

- A W^*-algebra is a C^*-algebra w/ a predual A_*

$$\iota: (A_*)^\vee \xrightarrow{\sim} A$$

(Normal linear functional's / density states)

Ex:

- $(B_1 \mathcal{H})^\vee \cong B\mathcal{H}$
- $(L^1(X, \mu))^\vee \cong L^\infty(X, \mu)$.
- Every F.d. C^*-algebra is W^*

<u>Def</u>: • A state on a C^*-algebra A is a $\underbrace{\text{positive linear functional}}_{\rho(a^*a) \geq 0}$

$$\rho : A \longrightarrow \mathbb{C}$$

(No normalization in this talk : i.e. $\rho(1)$ not nec. 1).

• A normal state on a W^*-algebra is an element of $(A_*)_+$

<u>Why?</u> $(A_*)^\vee \cong A \Rightarrow A_* \hookrightarrow (A_*{}^\vee)^\vee \xrightarrow{\sim} A^\vee$

<u>Ex</u>: • $\mathrm{Dens}(\mathcal{H}) \subseteq (B,\mathcal{H})_+$ $\quad A = B\mathcal{H}$

$$\hat{\rho} \rightsquigarrow \rho(-) = \mathrm{Tr}[\hat{\rho}(-)] : A \longrightarrow \mathbb{C}$$

• $L^1(X) \ni f \rightsquigarrow \mu_f : a \longmapsto \int_X a \, df$, $\quad a \in L^\infty(X)$

<u>The GNS-module</u>

A a C^*-alg. w/ unit ; $\rho : A \longrightarrow \mathbb{C}$ a state. Define:

$$\mathcal{I}_\rho = \{ a \in A : \rho(a^*a) = 0 \}$$

$$\overset{\text{Cauchy-Schwarz}}{=} \{ a \in A : \rho(x^*a) = 0 \ \forall x \in A \}$$

$$\mathrm{GNS}(\rho) = A/\mathcal{I}_\rho \ , \quad g_\rho = 1_A + \mathcal{I}_\rho$$

<u>Claim</u>: $\mathcal{I}_\rho$ is a left ideal $\Rightarrow$ $\mathrm{GNS}(\rho)$ is a left A-module.

$r \cdot a \in \mathcal{I}_\rho \ \forall r \in A$, $a \in \mathcal{I}_\rho$.

Interpretation:

- $GNS(\rho) =$ Right Essential equivalence classes of operators

$$a \overset{\text{r.e.c.}}{\sim} b \iff \rho(x^* a) = \rho(x^* b) \quad \forall x \in A.$$

Non-commutative analog of a.e. equiv functions
(take $a, b \in L^\infty(X)$).

Rmk: • $GNS(\rho)$ + Inner-prod $(a,b) \longmapsto \rho(a^* b)$ + Completion $\rightsquigarrow$ GNS - rep$^{\underline{n}}$
($L^2(X, \mu)$ in commutative theory)

- Can recover ρ from GNS-rep$^{\underline{n}}$: $\rho(x) = \langle g_\rho, x \cdot g_\rho \rangle$
- $A = B\mathcal{H} \Rightarrow$ Fits into a family of $L^{1/q}$-norms
$x \longmapsto Tr\left[|x \hat{\rho}^{1/q}|^q \right]^{1/q}$.

Submodules and Support Projections

Def: The support proj of a W^*-alg normal state $\rho : A \longrightarrow \mathbb{C}$
is the smallest self-adj. proj S_ρ s.t.

$$\rho(x S_\rho) = \rho(x) \quad \forall x \in A$$

(equiv. $\rho(S_\rho x) = \rho(x)$)

Ex: • $\hat{\rho} \in Dens(\mathcal{H})$; $S_\rho =$ Proj onto Image($\hat{\rho}$)

- μ: a measure on X ; "$S_\rho = 1_{\mu \neq 0}$"

Claim: • $\mathcal{I}_\rho = A(1 - S_\rho)$

- $$\begin{aligned} AS_\rho &\xrightarrow{\sim} GNS(\rho) \\ a &\longmapsto a + \mathcal{I}_\rho \end{aligned}$$

Cor: $\hat{\rho} \in \mathrm{Dens}(\mathcal{H}) \rightsquigarrow \mathrm{GNS}(\rho) \cong \mathcal{BH}\, S_\rho$

$\rho = \mathrm{Tr}[\hat{\rho}\,(-)]$

$$\cong \mathrm{Hom}^b(\mathrm{Image}(\hat{\rho}), \mathcal{H})$$

$$\underset{\substack{\text{Finite}\\ \text{dims}}}{\cong} \underset{\substack{\circlearrowleft \\ \mathcal{BH}}}{\mathcal{H}} \otimes \mathrm{Image}(\hat{\rho})^\vee$$

$$\left(\underset{\text{Basis}}{\cong} \mathcal{H}^{\oplus \mathrm{rank}(\hat{\rho})} \right)$$

PF that GNS-module is the smallest pointed module:

- ~~Show $\mathrm{GNS}(\rho_x) \cong \mathcal{H}_A \otimes \mathcal{H}_B / \underbrace{\mathrm{Ann}_{\mathcal{BH}_x}(\psi)}_{= \{a \in \mathcal{BH}_x : a \cdot \psi = 0\}}$~~

- ~~Look @ short exact sequence of complexes~~

~~$$\underbrace{K}_{\text{kernel}} \hookrightarrow \underbrace{M}_{\text{arbitrary}} \twoheadrightarrow \underbrace{G\psi}_{\text{Built From}} \; (\mathrm{GNS}(\rho_x), g_{\rho_x})$$~~

- Show that every morphism of pointed modules

$$f\;(M, m) \longrightarrow (N, n)$$

Factors through the "cyclification" of (N, n) uniquely

$$\begin{tikzcd} & (N/\mathrm{Ann}_A(n), n) \cong (A \cdot n, n) \arrow[d] \\ (M, m) \arrow[ur, dashed, "\exists !"] \arrow[r, "f"] & (N, n) \end{tikzcd}$$

- Show !-map is surjective

- Take $N \rightsquigarrow \mathcal{H}_A \otimes \mathcal{H}_B$

  $A \rightsquigarrow \mathcal{BH}_x$

- Show $\mathrm{GNS}(\rho_x) \cong \mathcal{H}_A \otimes \mathcal{H}_B / \mathrm{Ann}_{\mathcal{BH}_x}(\psi)$

- Look @ SES of Complexes

Arbitrary

$$0 \to K \longrightarrow M \longrightarrow G_\psi \longrightarrow 0$$

Kernel (via Componentwise Surjectivity) Built w/ GNS-module

- Show $H^1(K) = 0$

$$\Rightarrow \quad H^0(M) \cong H^0(G) \oplus H^0(K)$$

Constructing Multipartite Complexes

Multipartite State over Set of $\otimes$-Factors P:

$$\underline{\rho_P} = \left((A_s)_{s\in P},\ \rho_P : \bigotimes_{s\in P} A_s \longrightarrow \mathbb{C} \right)$$

<u>Claim:</u> $\underline{\rho_P} \overset{(A)}{\rightsquigarrow}$ Presheaf of $\mathbb{C}$-vector Spaces over P $\overset{\text{Čech}}{\underset{(B)}{\rightsquigarrow}}$ Cohomology

<u>(A)</u>: Define

$$G = G(\underline{\rho_P}) : \mathrm{Open}(P) \longrightarrow \mathrm{Vect}_{\mathbb{C}}$$

$\rho_T := \iota_T^* \rho : X \to \mathbb{C}$

$\iota_T : \bigotimes_{t\in T} A_t \to \bigotimes_{p\in P} A_p$

$$T \longmapsto GNS(\rho_T)$$

$$T \hookrightarrow V \longmapsto GNS(\rho_T) \longrightarrow GNS(\rho_V)$$

$$a \longmapsto \text{"}(a \otimes S_{V\setminus T})\text{"} S_V$$

<u>Claim:</u> This is a Functor:

$$G(T \hookrightarrow W \hookrightarrow V) = G(W \hookrightarrow V) \circ G(T \hookrightarrow V)$$

Want a map

$$T \hookrightarrow V \longmapsto GNS(\rho_T) \longrightarrow GNS(\rho_V)$$