

Measured Equivalence Relations

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March 9, 2023

Preliminary Definitions

Definition 1 (Measured Equivalence Relations). (X, μ) standard probability space. $\mathcal{R} \subseteq X \times X$ measurable equivalence relation .

- $[\mathcal{R}] = \{\phi \in \text{Aut}(X) : \text{graph}(\phi) \subseteq \mathcal{R}\}$
- \mathcal{R} is *probability measure preserving (pmp)* if $\mu \circ \phi = \mu$ for all $\phi \in [\mathcal{R}]$
- A pmp $[\mathcal{R}]$ is *ergodic* if $\mu(E) \in \{0, 1\}$ whenever $\mu(E \setminus \phi(E)) = 0$ for all $\phi \in [\mathcal{R}]$.

Given a positive measure subset, let $\mathcal{R}|_E$ denote the measured equivalence relation on $(E, \mu/\mu(E))$ given by $\mathcal{R}|_E = \mathcal{R} \cap (E \times E)$

Measured equivalence relations \mathcal{R}_i on (X_i, μ_i) for $i = 1, 2$ are *isomorphic* if there are full measure subsets $E_i \subseteq X_i$ which admit a measure space isomorphism $\phi : (E_1, \mu_1|_{E_1}) \rightarrow (E_2, \mu_2|_{E_2})$ such that

$$(x, y) \in \mathcal{R}_1|_{E_1} \iff (\phi(x), \phi(y)) \in \mathcal{R}_2|_{E_2}.$$

From now on, \mathcal{R} is a countable pmp equivalence relation on a standard probability space (X, μ) . Endow \mathcal{R} with a measure m given by

$$m(E) = \int_X |\{y \in [x]_{\mathcal{R}} : (x, y) \in E\}| d\mu(x) \text{ for all measurable } E \subseteq \mathcal{R}$$

Definition 2 (Equivalence Relation vNas).

$$\begin{aligned} g \in [\mathcal{R}] &\rightsquigarrow u_g \in \mathcal{U}(L^2(\mathcal{R}, m)) \text{ by } [u_g f](x, y) = f(g^{-1}x, y) \\ a \in L^\infty(X) &\rightsquigarrow a \in B(L^2(\mathcal{R}, m)) \text{ by } [af](x, y) = a(x)f(x, y) \end{aligned}$$

The von Neumann algebra of the equivalence relation \mathcal{R} is defined to be

$$L(\mathcal{R}) = (L^\infty(X) \cup \{u_g : g \in [\mathcal{R}]\})'' \subseteq B(L^2(\mathcal{R}, m))$$

$L(\mathcal{R})$ has a faithful normal trace given by $\tau(x) = \langle x \mathbb{1}_D, \mathbb{1}_D \rangle$ where $\mathbb{1}_D \in L^2(\mathcal{R}, m)$ is the indicator of the diagonal $D = \{(x, x) : x \in X\}$.

Let $Z^1(\mathcal{R}, S^1)$ denote the group of S^1 -valued multiplicative 1-cocycles on \mathcal{R} , i.e. the group of measurable maps $c : \mathcal{R} \rightarrow S^1$ such that for μ -a.e. $x \in X$,

$$c(x, z) = c(x, y)c(y, z) \text{ for all } (x, y), (y, z) \in \mathcal{R}.$$

Given $c \in Z^1(\mathcal{R}, S^1)$ and $g \in [\mathcal{R}]$, let $f_{c,g} \in \mathcal{U}(L^\infty(X))$ be given by $f_{c,g}(x) = c(x, g^{-1}x)$. Can check that the formula

$$\psi_c(au_g) = f_{c,g}au_g \text{ for all } a \in L^\infty(X), g \in [\mathcal{R}]$$

gives rise to a well defined *-isomorphism $\psi_c \in \text{Aut}(L(\mathcal{R}))$. Moreover, $c \mapsto \psi_c$ defines an action $\psi : Z^1(\mathcal{R}, S^1) \rightarrow \text{Aut}(L(\mathcal{R}))$.

Definition 3 (Hilbert Bundles). Given $\{\mathcal{H}_x\}_{x \in X}$ collection of Hilbert spaces, define the Hilbert bundle

$$X * \mathcal{H} = \{(x, \xi_x) : x \in X, \xi_x \in \mathcal{H}_x\}.$$

- A *section* ξ of the bundle $X * \mathcal{H}$ is a map $x \mapsto \xi_x \in \mathcal{H}_x$.
- *Fundamental sequence of sections* $\{\xi_n\}_{n=1}^\infty$ satisfy
 - $\mathcal{H}_x = \overline{\text{Span}\{\xi_n(x)\}_{n=1}^\infty}$ for each $x \in X$, and
 - the maps $\{x \mapsto \|\xi_n(x)\|\}_{n=1}^\infty$ are measurable.
- *Orthonormal fundamental sequence of sections* $\{\xi_n\}_{n=1}^\infty$ is a fundamental sequence of sections such that
 - $\{\xi_n(x)\}_{n=1}^\infty$ is an ONB of \mathcal{H}_x for $x \in X$ with $\dim(\mathcal{H}_x) = \infty$, and if $\dim(\mathcal{H}_x) < \infty$, the sequence $\{\xi_n(x)\}_{n=1}^{\dim(\mathcal{H}_x)}$ is an ONB and $\xi_n(x) = 0$ for $n > \dim(\mathcal{H}_x)$.

Now for measurable stuff

- *Measurable Hilbert bundle* $X * \mathcal{H}$ has σ -algebra generated by maps $\{(x, \xi_x) \mapsto \langle \xi(x), \xi_n(x) \rangle\}_{n=1}^\infty$.
- A *measurable section* of $X * \mathcal{H}$ is a section ξ such that $x \mapsto (x, \xi(x)) \in X * \mathcal{H}$ is a measurable map, or equivalently, such that the maps $\{x \mapsto \langle \xi(x), \xi_n(x) \rangle\}_{n=1}^\infty$ are measurable.
- $S(X * \mathcal{H})$ is the vector space of measurable sections up to μ -a.e. equivalence.
- The *direct integral*

$$\int_X^\oplus \mathcal{H}_x d\mu(x) = \{\xi \in S(X * \mathcal{H}) : \int_X \|\xi(x)\|^2 d\mu(x) < \infty\}$$

is a Hilbert space with inner product $\langle \xi, \eta \rangle = \int_X \langle \xi(x), \eta(x) \rangle d\mu(x)$.

- If $a \in A = L^\infty(X)$ and $\xi \in \int_X^\oplus \mathcal{H}_x d\mu(x)$ we denote by $a\xi$ or ξa the element of $\int_X^\oplus \mathcal{H}_x d\mu(x)$ given by $[a\xi](x) = [\xi a](x) = \xi(x)a(x)$.
- If $\{\xi_n\}_{n=1}^\infty$ orthonormal fundamental sequence of sections, any $\xi \in \int_X^\oplus \mathcal{H}_x d\mu(x)$ has an expansion $\xi = \sum_{n=1}^\infty a_n \xi_n$ where $a_n = \langle \xi(\cdot), \xi_n(\cdot) \rangle \in A$.

Representations

Definition 4 (Representations of Equivalence Relations). A *unitary* (resp. *orthogonal*) representation of \mathcal{R} on a complex (resp. real) measurable Hilbert bundle $X * \mathcal{H}$ is a map $(x, y) \mapsto \pi(x, y) \in \mathcal{U}(\mathcal{H}_y, \mathcal{H}_x)$ on \mathcal{R} such that for μ -a.e. $x \in X$, we have

$$\pi(x, z) = \pi(x, y)\pi(y, z) \text{ for all } (x, y), (y, z) \in \mathcal{R},$$

and such that $(x, y) \mapsto \langle \pi(x, y)\xi(y), \eta(x) \rangle$ is a measurable map on \mathcal{R} for all $\xi, \eta \in S(X * \mathcal{H})$.

- *Identity representation*: Given orthonormal fundamental sequence of sections $\mathcal{S} = \{\xi_n\}$, can form the *identity representation* $id_{\mathcal{S}}$ of \mathcal{R} on $X * \mathcal{H}$ by

$$id_{\mathcal{S}}(x, y)\xi_n(y) = \xi_n(x) \text{ for all } (x, y) \in \mathcal{R} \text{ and } \xi_n \in \mathcal{S}.$$

- *Regular representation*: Take $\mathcal{H}_x = l^2([x]_{\mathcal{R}})$ for each $x \in X$ and form $X * \mathcal{H}$ with fundamental sequence of sections $\{\xi_g\}_{g \in \Gamma}$ where
 - $\xi_g(x) = \mathbb{1}_{g^{-1}x}$ for all $x \in X$, and
 - Γ is a countable subgroup of $[\mathcal{R}]$ which generates $[\mathcal{R}]$ (FM75a showed this exists).

The *regular representation* of \mathcal{R} is the representation λ on $X * \mathcal{H}$ given by $\lambda(x, y) = id$ for all $(x, y) \in \mathcal{R}$.

We say representations π on $X * \mathcal{H}$ and ρ on $X * \mathcal{K}$ are *unitarily equivalent* if there is a family of unitaries $\{U_x \in \mathcal{U}(\mathcal{H}_x, \mathcal{K}_x)\}_{x \in X}$ with

$$U_x \pi(x, y) = \rho(x, y) U_y \text{ for all } (x, y) \in \mathcal{R},$$

and such that $x \mapsto U_x \xi(x)$ is in $S(X * \mathcal{K})$ for each $\xi \in S(X * \mathcal{H})$.

Cohomology

Definition 5 (1-cohomology).

- A *1-cocycle* for a representation π on $X * \mathcal{H}$ is a map $(x, y) \mapsto b(x, y) \in \mathcal{H}_x$ on \mathcal{R} such that for μ -a.e. $x \in X$,

$$b(x, z) = b(x, y) + \pi(x, y)b(y, z) \text{ for all } (x, y), (y, z) \in \mathcal{R},$$

and such that $(x, y) \mapsto (x, b(x, y)) \in X * \mathcal{H}$ is measurable.

- A 1-cocycle b is a *coboundary* if there is a $\xi \in S(X * \mathcal{H})$ such that

$$b(x, y) = \xi(x) - \pi(x, y)\xi(y) \text{ for } m\text{-a.e. } (x, y) \in \mathcal{R}.$$

- A pair of 1-cocycles b, b' are *cohomologous* if $b - b'$ is a coboundary.
- A 1-cocycle is *bounded* if there exists a sequence of measurable subsets $(E_n)_{n=1}^{\infty}$ of X with

$$\mu\left(\bigcup_{n=1}^{\infty} E_n\right) = 1 \text{ and } \sup\{\|b(x, y)\| : (x, y) \in \mathcal{R}|_{E_n}\} < \infty \text{ for each } n \geq 1.$$

Lemma 1. A 1-cocycle b for a representation π of $X * \mathcal{H}$ is a coboundary if and only if it is bounded.

Lemma 2 (Characterization for unboundedness). A 1-cocycle b for a representation π of $X * \mathcal{H}$ is unbounded if and only if there is a $\delta > 0$ such that for any $R > 0$ there is a $g \in [\mathcal{R}]$ with $\mu(\{x \in X : \|b(x, g^{-1}x)\| > R\}) \geq \delta$.

Orbit Equivalence Relations

Definition 6 (OE Relation). Given countable group Γ and pmp action $\Gamma \curvearrowright X$, the *orbit equivalence relation* $\mathcal{R}(\Gamma \curvearrowright X)$ is defined by

$$(x, y) \in \mathcal{R}(\Gamma \curvearrowright X) \iff y = gx \text{ for some } g \in \Gamma,$$

and two group actions are *orbit equivalent* (OE) if and only if they have isomorphic orbit equivalence relations.

Recall that $\Gamma \curvearrowright (X, \mu)$ is *free* if $\mu(\{x \in X : gx = x\}) = 0$ for each nonidentity $g \in \Gamma$.

If $\mathcal{R} = \mathcal{R}(\Gamma \curvearrowright X)$ for a free pmp action of a countable group Γ , then any group representation π gives rise to a representation $\pi_{\mathcal{R}}$ of \mathcal{R} , and any 1-cocycle b for π gives rise to a 1-cocycle $b_{\mathcal{R}}$ for $\pi_{\mathcal{R}}$. Note that

$$E_0 := \{x \in X : gx = x \text{ for some } g \in \Gamma \setminus \{e\}\} = \bigcup_{g \in \Gamma \setminus \{e\}} \text{Stab}_X(g)$$

is null since Γ is countable and the action is (essentially) free. Then the representation and cocycle are given as follows

- $\pi_{\mathcal{R}}(x, g^{-1}x) = \pi(g)$ for all $g \in \Gamma$
- $b_{\mathcal{R}}(x, g^{-1}x) = b(g)$ for all $g \in \Gamma, x \notin E_0$,

and since $\mu(E_0) = 0$, for $x \in E_0$ take $\pi(x, y) = id$ and $b(x, y) = 0$. Can check that $\pi_{\mathcal{R}}$ is mixing if and only if π is mixing and $b_{\mathcal{R}}$ is unbounded if and only if b is unbounded. This association also respects weak containment. When π is either left or right regular representation, $\pi_{\mathcal{R}}$ is unitarily equivalent to the regular representation λ .

Gaussian Construction

π orthogonal representation of \mathcal{R} on a real Hilbert bundle $X * \mathcal{H}$, $\{\xi_n\}_{n=1}^{\infty}$ orthonormal fundamental sequence of sections.

$$(\Omega_x, \nu_x) := \prod_{i=1}^{\dim(\mathcal{H}_x)} \left(\mathbb{R}, \frac{1}{\sqrt{2\pi}} e^{-s^2/2} ds \right)$$

Define $\omega_x : \text{Span}(\{\xi_i\}_{i=1}^{\dim(\mathcal{H}_x)}) \rightarrow \mathcal{U}(L^\infty(\Omega_x))$ by

$$\omega_x \left(\sum_{n=1}^k a_n \xi_{i_n}(x) \right) = \exp \left(i\sqrt{2} \sum_{n=1}^k a_n S_{i_n}^x \right),$$

where S_j^x is the j -th coordinate function for $j \leq \dim(\mathcal{H}_x)$. Then ω_x extends to $\omega_x : \mathcal{H}_x \rightarrow \mathcal{U}(L^\infty(\Omega_x))$ such that

- $\tau(\omega_x(\xi)) = e^{-\|\xi\|^2}$
- $\omega_x(\xi + \eta) = \omega_x(\xi)\omega_x(\eta)$
- $\omega_x(\xi)^* = \omega_x(-\xi)$.

$D_x := \text{Span}_{\mathbb{C}}(\{\omega_x(\xi)\}_{\xi \in \mathcal{H}_x})$ has $D_x'' = \overline{D_x}^{WOT} = L^\infty(\Omega_x)$.

For $(x, y) \in \mathcal{R}$, define a *-homomorphism $\rho(x, y) : D_y \rightarrow L^\infty(\Omega_x)$ by

$$\rho(x, y)\omega_y(\xi) = \omega_x(\pi(x, y)\xi),$$

which is well defined and $\|\cdot\|_2$ -isometric since

$$\tau(\omega_y(\eta)^* \omega_y(\xi)) =$$

Facts

Note that given a representation π of \mathcal{R} , we can get a group representation $\tilde{\pi} : [\mathcal{R}] \rightarrow \mathcal{U} \left(\int_X^{\oplus} \mathcal{H}_x d\mu(x) \right)$ by

$$[\tilde{\pi}(g)\xi](x) := \pi(x, g^{-1}x)\xi(g^{-1}x)$$

- According to <https://ncatlab.org/nlab/show/measurable+field+of+Hilbert+spaces>, the category of measurable Hilbert bundles on (X, Σ, N) is equivalent to the category of Hilbert $L^\infty(X, \Sigma, N)$ -modules. I assume this is through the direct integral being an L^∞ -module.
- **TODO** Try to encode representations of $L(\mathcal{R})$ in this framework.

Work

Coproduct shit

Definition 7. Let \mathcal{R} be a countable pmp equivlence relation on a standard probability space (X, μ) . A subequivalence relation $\mathcal{S} \subseteq \mathcal{R}$ is called *full* if $(x, x) \in \mathcal{S}$ for all $x \in X$, i.e. \mathcal{S} is also an equivalence relation over X .

Lemma 3. *Let \mathcal{R} be a countable pmp equivlence relation on a standard probability space (X, μ) , and $N \subseteq L(\mathcal{R})$ a unital von Neumann subalgebra such that $L^\infty(X) \subseteq N$. Consider the relative coproduct on $L(\mathcal{R})$ given by*

$$\begin{aligned} \Delta : L(\mathcal{R}) &\rightarrow L(R) \overline{\otimes} L(R) \\ au_g &\mapsto au_g \otimes u_g. \end{aligned}$$

Then $\Delta(N) \subseteq N \overline{\otimes} N$ if and only if there exists a (full?) subequivalence relation $\mathcal{S} \subseteq \mathcal{R}$ such that $N = L(\mathcal{S})$.

Proof.

\implies : Suppose that $\Delta(N) \subseteq N \overline{\otimes} N$. Let

$$S = \{g \in [\mathcal{R}] : \exists a \in A \text{ such that } \tau(au_g^*) \neq 0\}.$$

\impliedby :

□