Poincaré Duality Angles on Riemannian Manifolds with Boundary

Clayton Shonkwiler

Department of Mathematics
University of Pennsylvania

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Realizing cohomology groups as spaces of differential forms

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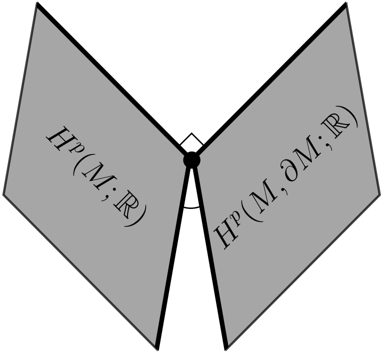

de Rham's Theorem

Suppose M^n is a compact, oriented, smooth manifold. Then

$$H^p(M; \mathbb{R}) \cong \mathcal{C}^p(M)/\mathcal{E}^p(M),$$

where $\mathcal{C}^p(M)$ is the space of closed p-forms on M and $\mathcal{E}^p(M)$ is the space of exact p-forms.

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Kodaira called this the space of *harmonic p-fields* on M.

Hodge's Theorem

If M^n is a closed, oriented, smooth Riemannian manifold,

$$H^p(M;\mathbb{R}) \cong \mathcal{H}^p(M).$$

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Then

$$H^p(M; \mathbb{R}) \cong \mathcal{H}^p_N(M).$$

Hodge–Morrey–Friedrichs Decomposition (continued)

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Non-orthogonality

The concrete realizations of $H^p(M;\mathbb{R})$ and $H^p(M,\partial M;\mathbb{R})$ meet only at the origin:

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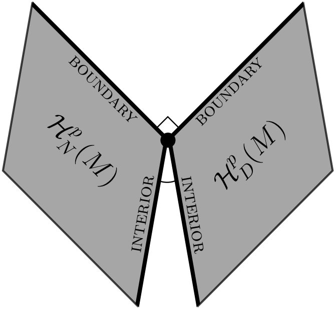

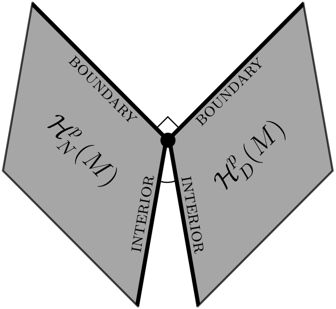

Definition (DeTurck–Gluck)

The *Poincaré duality angles* of the Riemannian manifold M are the principal angles between the interior subspaces.

What do the Poincaré duality angles tell you?

Guess

If M is "almost" closed, the Poincaré duality angles of M should be small.

Consider $\mathbb{CP}^2$ with its usual Fubini-Study metric. Let $p \in \mathbb{CP}^2$. Then define

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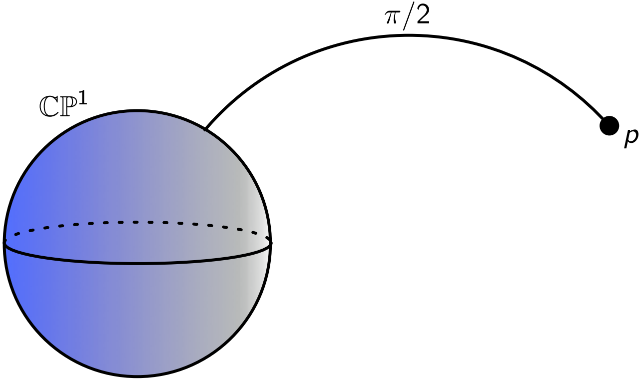

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Topology of M_r

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M_r is the D^2-bundle over $\mathbb{CP}^1$ ($\simeq S^2(1/2)$) with Euler characteristic 1.

M_r has absolute cohomology in dimensions 0 and 2.

M_r has relative cohomology in dimensions 2 and 4.

Therefore, M_r has a single Poincaré duality angle θ_r between $\mathcal{H}^2_N(M_r)$ and $\mathcal{H}^2_D(M_r)$.

So the goal is to find closed and co-closed 2-forms on M_r which satisfy Neumann and Dirichlet boundary conditions.

Find harmonic 2-fields

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Find closed and co-closed $SU(2)$-invariant forms on M_r satisfying Neumann and Dirichlet boundary conditions

The Poincaré duality angle for M_r

$$\cos\theta_r = \frac{1 - \sin^4 r}{1 + \sin^4 r}.$$

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Generalizes to $\mathbb{CP}^n - B_r(p)$.

Consider

$$N_r := G_2\mathbb{R}^n - \nu_r(G_1\mathbb{R}^{n-1}).$$

Poincaré duality angles of Grassmannians

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Theorem

- *As $r \to 0$, all the Poincaré duality angles of N_r go to zero.*
- *As r approaches its maximum value of $\pi/2$, all the Poincaré duality angles of N_r go to $\pi/2$.*

Conjecture

If M^n is a closed Riemannian manifold and N^k is a closed submanifold of codimension ≥ 2, the Poincaré duality angles of

$$M - \nu_r(N)$$

go to zero as $r \to 0$.

What can you learn about the topology of M from knowledge of ∂M?

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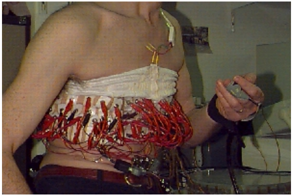

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If γ is the conductivity on M, the current flux through ∂M is given by

$$(\gamma \nabla u) \cdot \nu = -\gamma \frac{\partial u}{\partial \nu}$$

The map $\Lambda_{\mathrm{cl}} : C^\infty(\partial M) \to C^\infty(\partial M)$ defined by

$$f \mapsto \frac{\partial u}{\partial \nu}$$

is the classical *Dirichlet-to-Neumann map*.

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Theorem (Lee-Uhlmann)

If M^n is a compact, analytic Riemannian manifold with boundary, then M is determined up to isometry by Λ_{cl}.

Generalization to differential forms

Joshi–Lionheart and Belishev–Sharafutdinov generalized the classical Dirichlet-to-Neumann map to differential forms:

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Theorem (Belishev–Sharafutdinov)

The data $(\partial M, \Lambda)$ completely determines the cohomology groups of M.

Define the *Hilbert transform* $T := d\Lambda^{-1}$.

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Theorem

If $\theta_1, \ldots, \theta_k$ are the Poincaré duality angles of M in dimension p, then the quantities

$$(-1)^{np+n+p} \cos^2 \theta_i$$

are the non-zero eigenvalues of an appropriate restriction of T^2.

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Theorem

The mixed cup product

$$\cup : H^p(M;\mathbb{R}) \times H^q(M,\partial M;\mathbb{R}) \to H^{p+q}(M,\partial M;\mathbb{R})$$

is completely determined by the data $(\partial M, \Lambda)$ when the relative class is restricted to come from the boundary subspace.

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- What is the limiting behavior of the Poincaré duality angles as the manifold "closes up"?
- Can the full mixed cup product be recovered from $(\partial M, \Lambda)$? What about other cup products?
- Can the L^2 inner product on $\mathcal{H}^p_N(M)$ and $\mathcal{H}^p_D(M)$ be recovered from $(\partial M, \Lambda)$?

Thanks!